UNIVERSITY OF ALBERTA

AN INTEGRATED ICHNOLOGICAL PERSPECTIVE FOR CARBONATE DIAGENESIS

BY

ARJUN DIPCHAND KESWANI ©

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It is not possible to solve a problem
within the same consciousness that produced it.

- ALBERT EINSTEIN

The real voyage of discovery
consists not in seeking new landscapes,
but in having new eyes.

- MARCEL PROUST

Science is the knowledge of consequences,
and dependence of one fact upon another.

- THOMAS HOBBES

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THE UNDERSIGNED CERTIFY THAT THEY HAVE READ, AND RECOMMEND TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH FOR ACCEPTANCE, A THESIS ENTITLED **AN INTEGRATED ICHNOLOGICAL PERSPECTIVE FOR CARBONATE DIAGENESIS**, SUBMITTED BY ARJUN DIPCHAND KESWANI IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT

An ichnologic-sedimentologic study of the subsurface Mississippian Midale Beds, in the Radville area, Saskatchewan, shows two distinct textural facies associations in carbonate detritus: a muddy facies association and a bioclastic facies association. Trace fossil suites, typical of the *Cruziana* ichnofacies characterized these sedimentary facies associations, respectively: (1) a distal *Cruziana* ichnocoenose, and (2) a proximal *Cruziana* ichnocoenose. Such physical and paleobiological data suggest deposition in a deep subtidal, quiescent outer-to-inner shelf marine environment, influenced episodically by high-energy storm regimes. These subtidal deposits showed an overall shallowing-upward trend, where regression culminated in progradation of the sabkha, and in restricted intertidal paleoenvironments.

To understand the nature of intrinsic paleobiological controls on diagenetic mechanisms, behavioural dynamics manifested in both discrete trace fossils and indiscrete bioturbate textures have been modelled as equivalent genetic entities that influenced fabric evolution. This represents an extension of genetic principles inherent in the ichnofacies concept to indiscrete bioturbate textures, and an integrated ichnological perspective for modelling effects of bioturbation. Such genetic requirements for indiscrete bioturbate textures prompted a review of previous classification schemes and applications. This review showed inconsistencies in use of terminology; and simple, descriptive, semiquantitative, and complex mathematical and computer-based models lacked biologically-significant criteria as the basis of classification, which rendered the ichnofabric concept genetically incongruous to the ichnofacies model. To rectify this incompatibility, a conceptual model depicted an hierarchy for the equivalence of discrete trace fossils in ichnofacies and indiscrete bioturbate textures in the genetic-spatiotemporal frameworks proposed and restricted scales of applications to outcrop/drill core studies and to petrographic analysis, respectively.

Integration of ichnological parameters facilitated construction of a comprehensive model for texture genesis and diagenesis. The proposed model consists of conceptual frameworks for genetic and spatiotemporal relationships manifested in both the physical and mineralogical characteristics of fabrics and textures. Correlations of unique and overlapped spatiotemporal dimensions on (1) paleobiologically-sedimentologically-, and on (2) diagenetically-significant scales links genetic aspects of paleoecological-geochemical dynamics in textural evolution.

DEDICATION

This thesis is dedicated to my beloved parents, my mother Meryl Hiett Keswani and to my late father, Dr. D.G. Keswani. I will be forever grateful to my parents for their foresight, hard work and sacrifices to bring our family to Canada, and to give me opportunities that I would not have enjoyed otherwise. The love, support, understanding and encouragement my parents bestowed, gave me the courage and confidence to take advantage of the opportunities our wonderful adopted country offered. I would not be the man I am today without the contribution my parents have made to enrich my life. I salute my parents, for they are a part of every effort and success in my life. All my love.

ACKNOWLEDGEMENTS

In modern scientific research, our arduous journey in the search for the truth requires opportunity, inspiration, time, and above all, passion. These elements set the stage for ideas to be developed, where personal philosophy and experiences influence considerably the nature of truths derived in research. These truths form merely part of a continuum of ideas that have evolved through history. Therefore, I must pay homage to those who made my research possible, especially to my supervisor Dr. S. George Pemberton who had that special foresight to recognize the potential and passion in me, and to provide the opportunity and inspiration necessary.

George is the only Professor of Geology who ***really*** understands me and knows how to supervise me. George had the faith and patience in me to work toward the development of another generation of truths in the evolutionary stages that constitute scientific research. George's unwavering belief in me, and the freedom he gave me were instrumental factors in the successful pursuit of my passion for science. George believed in me, when few others did; even myself, at times. For George's faith and patience in me, and for the opportunity to pursue my passion for research in paleoecology and paleontology, I will be eternally grateful. I thank George from the bottom of my heart for the priviledge to work for him, and for the opportunity to conduct scientific research. Indeed, his supervision, guidance and financial support are deeply appreciated. I am in awe of George's breadth of knowledge on ichnology, paleontology, paleoecology, sedimentology, and marine biology and ecology. Is it any wonder that George is such an inspirational figure to me?

However, my admiration of George extends beyond the professional realm. I know the **REAL** George Pemberton, both outside and inside. My reflections on George's personal history leaves me astounded. The obstacles he faced, and yet triumphed is truly inspirational to me. I can relate personally to much of what George has faced. At times, I see myself in the same shoes that George has walked. His personal triumphs gives me hope that hard work and perserverence in scientific endevours are worthwhile. Yet, the success George enjoys presently has not changed fundamentally, the decent, compassionate and down-to-earth man he has always been. He will always be a "students'" professor. George's humility deserves equal recognition in defining the inspirational qualities of his personal attributes. These attributes, both personal and professional, has left one overall impression on my mind: I am a very lucky man because George has touched my life! I feel truly honoured to be one of George's graduate students.

A thesis is rarely the product of a graduate student-supervisor relationship alone. It is a product of supportive contributions from colleagues, friends and family, also. My supporters include many fine graduate students both past and present in the Ichnology Research Group, and friends at the University of Alberta in Edmonton; Saskatchewan Energy and Mines, Saskoil and consultants in Regina, and my family. A number of fellow graduate students from the Ichnology Research Group have encouraged me in my work through the past several years. I express my deep appreciation to Dr. James MacEachern (Simon Fraser University) for introducing me to the carbonates in the subsurface of Saskatchewan, and for his assistence in teaching me how to recognize biogenic sedimentary structures, and for core photography in early stages of research. I extend gratitude to Tom Saunders and Murray Gingras for sharing their passion and enthusiasm for research in marine ecology, biology and ichnology. Tom and Murray's passion and enthusiasm was both inspirational and very contagious! At times, these were the only motivations that kept me going. Also, I would like to thank other members of the ichno-group, especially Dr. Mike Ranger, John Bourak, Howard Brekke, Dave Bechtel, Mike Gier, Indy Raychadhuri, Demian Robbins, Stephen Hubbard, Eric Hanson, and Jason Lavigne for their friendship, advice, help, and mostly for the laughs we shared over a nice cold beer! Furthermore, Dr. Mike Ranger is gratefully acknowledged for use of his AppleCore logging program.

Specific chapters in my thesis benefitted from the input of many colleagues and associates. These individuals are gratefully acknowledged for their unique contributions. **Chapter 2**. Paul Blanchon and Indraneel Raychadhuri are thanked for suggesting numerous improvements to the original manuscript. Ian Hunter and Howard Brekke are acknowledged with thanks for their suggestions on some technical aspects of the study and preparation of the manuscript. Dr.Brian Jones (University of Alberta) is acknowledged with gratitude for providing access to the carbonate research facilities at the university farm during the early stages of my research. **Chapter 3**. I am grateful to Tom Saunders, Murray Gingras, Demian Robbins, and Bruce Beynon for permission to use photographs for comparative analysis of bioturbate textures developed in various paleoenvironmental and stratigraphic settings. **Chapter 4**. I am grateful to fellow colleagues for suggestions which improved the illustration of the concepts presented in this chapter: Dr. O.A. Dixon (Department of Earth Sciences, University of Ottawa) for the idea of representing genetic aspects in a three-dimensional framework; and Drs. Michael Caldwell and W. George Evans (Department of Biological Sciences, University of Alberta) for reviews of paleobiological relationships shown in the spatiotemporal framework.

I acknowledge with gratitude the contributions of both individuals and organizations in Regina, who made this work possible. I thank Saskatchewan Energy & Mines for providing access to the core research facilities at the Subsurface Geological Laboratory. Specifically, I am deeply grateful to Fran Haidl for her assisstance in the early stages of my study. Her help ensured my work proceded on a sound foundation. I extend thanks to Jim Arthur for introducing me to the Midale Beds and other Mississippian carbonates, and for his time and efforts in showing me some of the fundamental aspects of the petroleum geology of Saskatchewan. Dr. Don Kent (University of Regina) is thanked for sharing some of his insights on carbonate deposits in the Williston Basin. The combined contributions of these individuals enhanced my understanding of carbonate sedimentology and hydrocarbon potential of ancient deposits in Saskatchewan. Yes, Saskatchewan is a great place to study petroleum geology! This field area offers both challenges and opportunities!

I would like to take this opportunity to thank others who contributed to my research, and in communicating the results. I am grateful to Dr. B. Mamet (Université de Montréal) for sharing some of his insights on the taxonomic aspects of Mississippian calcareous algae and their paleoenvironmental significance. Also, I thank Randy Pakan (University of Alberta) for assistance in preparation of professional quality slides and for

his advice on overcoming computer problems related to software compatibility between old and new graphic files.

A few words about Don Resultay cannot be ommitted in these acknowledgements. Not only does Don make the best thin-sections I have ever seen, he sure makes a good friend, too! Don's technical excellence stems from his meticulosity and work ethic. Our department should be proud of Don's professional dedication. Also, I appreciate Don's technical advice and help with Macintosh computers and software, and with construction of my posters for conferences. This assistance contributed significantly to the professional quality of these presentations. But, Don's main contribution is in the friendship we share. His friendship, encouragement and support was instrumental in seeing me through the most painful and darkest hours of my life in the last two years. Don used his incredible insightfulness and observation skills, and his optimism and wacky sense of humour to keep me focused on what was important, and to give me hope and provide some perspectives during my time of need. His belief in me, and his genuine caring and support of me are the fundamental attributes of our frienship that I will always treasure. No words can begin to express the gratitude I feel for Don. Our friendship has greatly enriched my life!

I want to take this opportunity to thank the entire Pemberton family, and especially Teresa for her warm hospitality, and understanding. The Pemberton family made me feel welcome and "at-home" during my visits. This means a lot to me! Indeed, the Pembertons are really cool people!

Financial support is gratefully acknowledged from the Saskatchewan Oil & Gas Corpooration (now Wascana Energy/Canadian Occidental Petroleums), and a Province of Alberta Graduate Scholarship awarded to me. In addition, moneys were provided to me by my family, in support of my living expenses during the pursuit of my scientific passion. In particular, I thank my mother Meryl Keswani and my aunt Dhan Keswani for their generosity and acts of love. Furthermore, my study has been funded by the Natural Sciences and Engineering Research Council of Canada, Grant No. A0816 to Dr. S. George Pemberton.

The work of scientific discovery is never complete. The fossil record still presents opportunities for another story to be told, and another chapter to be written in the storybook that represents our understanding of the splendor of life in earth history. The organisms preserved in the fossil record must be brought alive once again! These animals have a story to tell about their lives, their evolution, earth history, and indeed, about ourselves! I express my deep appreciation to George for yet another opportunity to continue my paleoecological research at the University of Alberta. Indeed, his confidence in me is both uplifting and humbling! The work of science continues!

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CHAPTER 1

INTRODUCTION

Analysis of discrete trace fossils and indiscrete bioturbate textures, and associated diagenetic fabrics in detrital carbonates provide, the basis of understanding the nature of linkages in fabric genesis and diagenesis. An holistic approach in textural analysis based on genetic criteria, facilitates interpretations of both direct and indirect roles of paleobiological processes on geochemical mechanisms. These include the effects of bioturbate textures on the changes in developments of diagenetic fabrics. This concept of fabric evolutionary dynamics provides a useful fundamental base for interpretations of genetic relationships manifested in physical and mineralogical characteristics of bioturbated substrates.

This thesis presents the initial results derived in a dual-stage research program focused on the problem of intrinsic paleobiological controls on diagenesis. Abundance of bioturbate textures in the Mississippian Midale carbonates of the Williston Basin, southern Saskatchewan, represented substrates suitable for detailed study of such relationships in paleoecological-geochemical dynamics. This research program is designed to examine systematically, the effects of contemporaneous biotic processes on both early- and late-stage diagenesis. Such a systematic approach consists of two phases of investigation: (1) construction of a conceptual model for study of genetic linkages in textural evolutionary dynamics; and (2) subsequent applications in both sedimentologic and diagenetic studies of stratigraphically-diverse carbonate deposits. This latter phase represents a continuation of research toward understanding genetic linkages between bioturbation and diagenesis, particularly the effects of specific paleoecological interactions on origins and distribution patterns in dolomites.

The traditional ichnofacies concept applied in paleoenvironmental reconstruction, and paleoecological interpretations, provided the genetic foundation for the initial stage of research. This phase of research is focused on utilizing discrete trace fossils, and on classifying indiscrete bioturbate textures, by integrating both paleobiological aspects provide a more complete picture of paleoecological dynamics. This approach included integration of sedimentological and ichnological data from core descriptions, and from conventional petrographic analysis. Since physical and mineralogical parameters represent characteristics associated inherently with bioturbate textures, integration of data on diagenetically-and paleobiologically-significant processes, facilitates interpretations of paleoecological controls on geochemical mechanisms. But, an understanding of relationships inherent in paleoecological-geochemical dynamics requires a comprehensive model for texture genesis and diagenesis. In such a conceptual model, aspects of origins in both discrete trace fossils and indiscrete biogenic fabrics necessitates congruence in philosophical perspectives in classsifications, and restricted boundary conditions for scales of observations, and for genetic applications. Such an extension of genetic principles inherent in the ichnofacies concept, prompted a review of previous classification schemes for indiscrete bioturbate textures.

The usefulness of previous classification schemes in genetic applications is reviewed. Scrutiny of these schemes show a fundamental flaw: absence of biological criteria as a basis for classification, and problems related to scales in applications. These genetic inconsistencies and scale discrepancies limited the usefulness of prior classification schemes. Consequently, this ongoing research addresses the problem of establishing a genetic classification scheme for indiscrete bioturbate textures.

A compelling problem remains: how to establish genetic linkages in paleoecological-geochemical dynamics? These links in texture genesis and diagenesis include the effects of many processes at diverse spatiotemporal scales. To rectify this problem, a conceptual model for textural evolution is proposed. This model integrated data from core/outcrop studies and petrographic analysis. Such an evolutionary model provided cohesiveness for genetic elements produced at various spatiotemporal scales, and facilitated interpretations of controls on textural origins. The model linked the cumulative effects of processes in textural evolution, including those produced diachronously. This approach facilitates erection of a new classification scheme for bioturbate textures in a separate paper. Furthermore, the proposed genetically-significant categories for biogenic fabrics and textural relationships represent integrative elements in the conceptual model. Such genetic compatibility provides a powerful tool useful for interpretations of intrinsic paleobiological controls on textural origins, particularly on developments of potential economically-significant dolomite fabrics.

CHAPTER 2

SEDIMENTOLOGY, ICHNOLOGY, AND PALEOECOLOGY OF THE MISSISSIPPIAN MIDALE CARBONATES IN THE WILLISTON BASIN, RADVILLE AREA,SASKATCHEWAN: PRELIMINARY INTERPRETATIONS[1]

INTRODUCTION

Ichnological features such as discrete trace fossils, indiscrete bioturbate textures and bioerosion structures are very common biological aspects in both ancient and modern carbonate depositional environments. Yet, the ichnology of these sedimentary environments is poorly known. Relatively few studies have focused on these biogenic structures emplaced in both soft and hard substrates (Shinn, 1968; Garret, 1977; Hardie and Ginsburg, 1977; Fursich, 1977; James *et al.*, 1977; Kobluk *et al.*, 1978; Brett and Liddell, 1978; Archer, 1984; Curran, 1984, 1994; Narbonne 1984; Pickerill *et al.*, 1984; Hoffman, 1985; Pleydell, 1987; Pleydell and Jones, 1988; Pemberton *et al.*, 1988; Wanless *et al.*, 1988; Jones and Pemberton, 1989; Curran and White, 1991; Vogel, 1993; Bromley, 1994; Demicco and Hardie, 1994). These studies have documented the sedimentological distribution patterns of biogenic structures, and their diagenetic and taphonomic characteristics. However, this study applies the ichnofacies concept to understand the nature of organism-sediment interactions recorded in the distribution patterns of trace fossil assemblages. This concept provides a foundation for expansion of genetic principles to indiscrete textures. Such an integrated approach facilitates a more complete picture of the roles of biotic processes in shaping the overall diagenetic characteristics of detrital carbonate accumulations. The abundance of bioturbate textures, including well-preserved ichnofossils and indiscrete fabrics renders the Mississippian Midale carbonates in the Radville area, an ideally suited unit for such an integrated study.

---

[1] A version of this chapter has been published. Keswani, A.D. and Pemberton, S.G., 1993. *In*: R. Karvonen, J. Den Haan, K. Jang, D. Robinson, G. Smith, T. Webb, J. Wittenberg, eds., Carboniferous to Jurassic Pangea, Core Workshop Guidebook, Canadian Society of Petroleum Geologists, Calgary, p. 206-228.

STRATIGRAPHIC SETTING AND BASIN EVOLUTION

The middle-Mississippian Midale Beds deposited on the northeast flank of the intracratonic Williston Basin, form some of the most prolific hydrocarbon reservoirs in southeastern Saskatchewan (Smith, 1980). The study area (Figure 1) is situated south of the "Midale Trend" which subcrops in the south-central to southeastern portions of Saskatchewan (Smith, 1980). Midale Beds are thought to be equivalent to the uppermost units of the Mission Canyon Formation (Figure 2). But, these carbonate deposits have also been suggested to belong to the basal part of the Charles Formation (Crabtree, 1982; Matiisen and Shehata, 1987; Kerr, 1988, and Lake, 1991).

Midale Beds are composed of the basal Frobisher evaporite unit and the Midale carbonates (Smith, 1980; Kent, 1984). The Midale carbonates may be further subdivided into a lower, middle, upper and uppermost units (Fuzesy, 1960; Smith, 1980). On an informal basis the carbonates are subdivided into an upper "marly" unit and a lower "vuggy" unit (Matiisen and Shehata, 1987). The carbonates are capped by the Midale evaporite unit that completes the Midale shallowing-upward cycle within lower Ratcliffe Beds or the equivalent lower Charles Formation (Smith, 1980; Lake, 1991).

Midale Beds are equivalent to the uppermost Mission Canyon Formation (middle succession of the Madison Group, Figure 2). This group constitutes the greater part of the 600 m thick Mississippian sequence consisting of alternating carbonate/dolostone and evaporite beds deposited on the northern Williston Basin (Kent, 1984a). The Madison Group is interpreted as a large-scale shallowing upward sequence from deep-water basin carbonates (Waulsortian-type mounds of the Lodgepole Formation and its equivalent Souris Valley Beds), through shallow marine carbonates, to tidal flat carbonate-evaporites, which eventually culminates upward in sabkha evaporites above the Ratcliffe Beds (Smith, 1980; Kent, 1984a b, 1987a; Lake, 1991).

Mississippian strata are correlated using recurring evaporite marker beds. Regional stratigraphic correlation facilitated development of a basin model (Kent, 1984a, b, 1987a; Kent *et al.*, 1988). Early Mississippian sediments were likely deposited on a carbonate ramp setting, where basinal (anaerobic), lower slope (dysaerobic), upper slope and shelfal (aerobic) facies were recognized (Kent, 1984a, b, 1987a; Kent *et al.*, 1988). During the time of Mission Canyon deposition, oxygenated marine conditions prevailed as the margins of the Williston Basin evolved into a shallow shelf environment, and the Midale Beds were deposited (Kent, 1984a, b, 1987a; Kent *et al.*, 1988; Lake, 1991).

During the Osagean stage (middle Mississippian), the Midale-Ratcliffe carbonates were deposited in paleoenvironments that varied from basinal through shelfal to peritidal settings (Smith, 1980; Lindsay and Roth, 1982; Kent, 1984a, b, 1987a; Kent *et al.*, 1988). These deposits formed parts of four transgressive-regressive cycles in the Mission Canyon Formation (Lake, 1991). Frobisher-Alida-Midale Beds prograded westward during these transgressive pulses (Smith, 1980; Lindsay and Roth, 1982; Lake, 1991). These smaller-scale deepening-shallowing upward cycles in carbonate deposits form parts of the overall regressive Madison Group (Matiisen and Shehata; 1987; Kent *et al.*, 1988; Lake, 1991). Each minor cycle terminated with deposition of evaporites (Kent *et al.*, 1988). Tectonic subsidence of the basin was likely responsible for transgressive episodes and depositional cycles (Kent, 1987b). Post-Mississippian basin margin uplift and erosion resulted in a northwest-southeast arcuate subcrop trend of the Midale and other Mississippian cycles (Kent *et al.*, 1988).

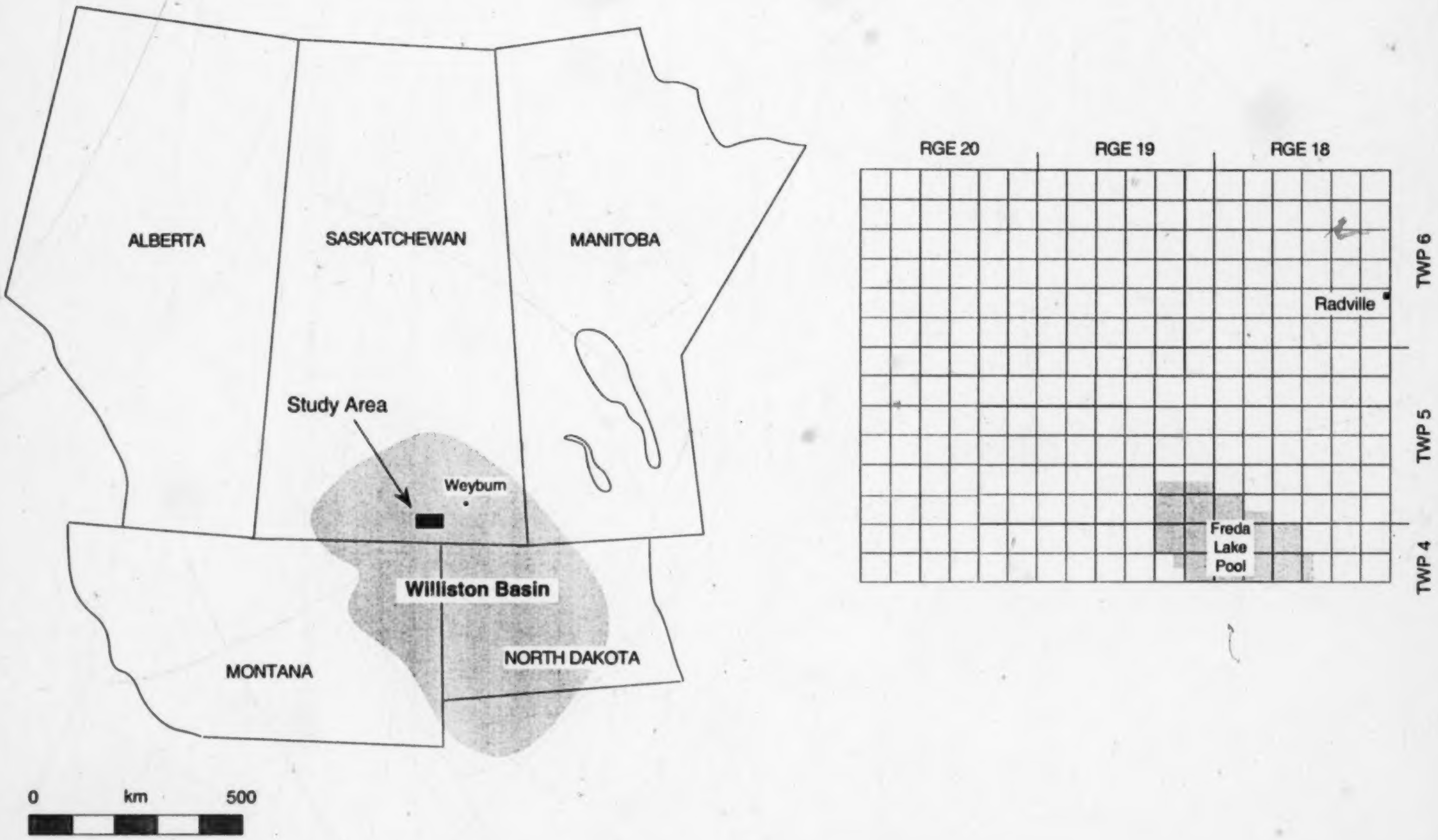


Figure 1. Location map of study area within the Williston Basin.

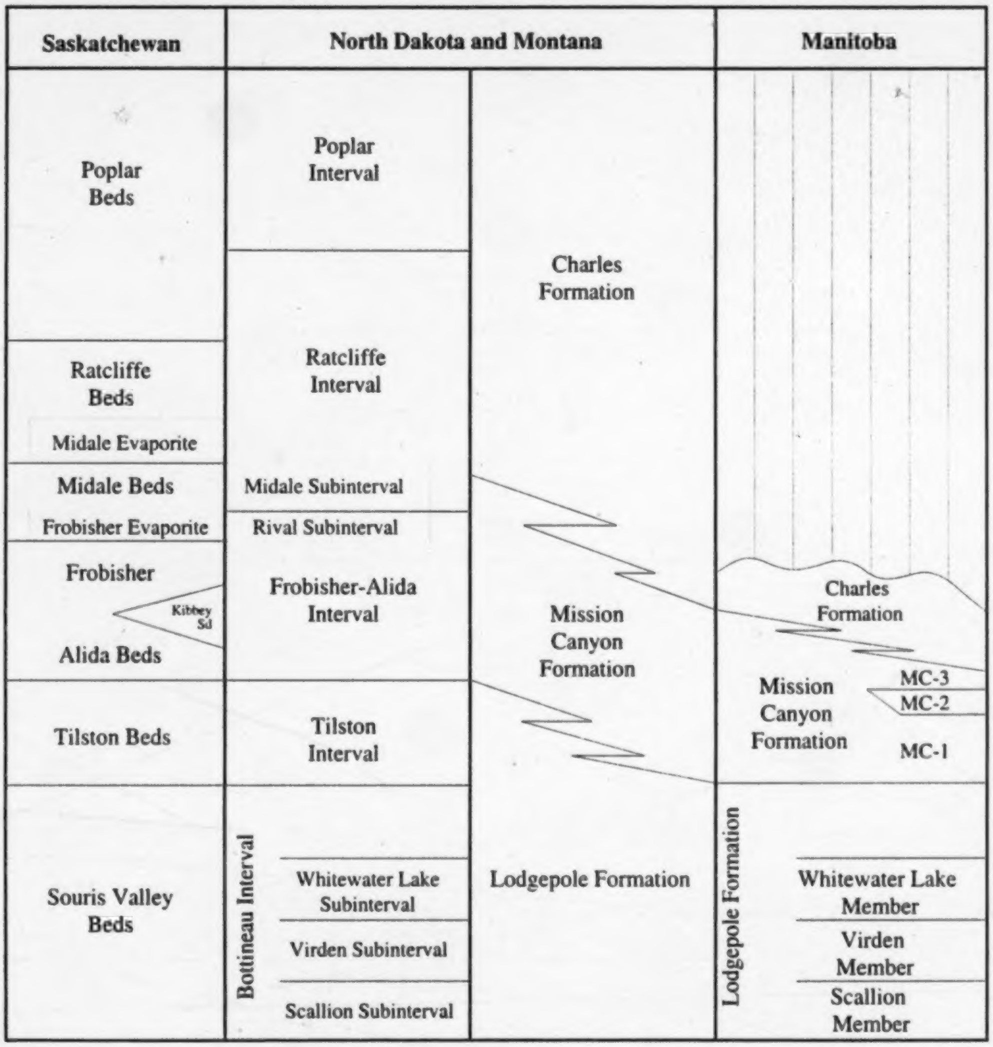


Figure 2. Commonly accepted Mississippian stratigraphic nomenclature for the Williston Basin (Kent, 1984a,b).

MIDALE FACIES ASSOCIATIONS

Twenty-four thin sections from core at 7-1-5-19W2 were examined in detail. Petrographic analysis included recording the variety and estimated volume of allochems, textural features and significant diagenetic features. Textural features included grain sizes, grain shapes, types of grain-to-grain contacts, and degree of sorting. Grain sizes were defined as fine, medium or coarse corresponding to <0.2 mm, 0.2-1.0 mm, and >1.0 mm classes. Samples were collected from representative units as well as multiple samples from portions of units of particular interest.

Vertical facies distribution, relevant paleontologic, ichnologic and sedimentologic characteristics of each rock unit are summarized in the litholog illustrated in Figures 3 and 4. The ichnology table accompanying the litholog shows distribution of discrete trace fossils and the trace fossil associations. The table indicates presence or absence of ichnofossils and has no affinity to their abundance. The body fossil or grain content shown in the litholog refers to components that contribute 5% or more to the unit volume.

Based on petrographic analysis of texture, five facies were recognized and named according to Dunham's (1962) classification scheme. These textural types are dolomudstone, skeletal dolowackestone, skeletal wackestone, peloidal-skeletal packstone and peloidal-skeletal grainstone. These textural units were combined into two general facies associations for the cored well 7-1-5-19W2: (1) a muddy facies association and (2) a bioclastic facies association.

MUDDY FACIES ASSOCIATION

The dolomudstone units are a non-fossiliferous facies composed of 80%-95% dolomicrite. Organic content averages 1%-3% and may reach 5% in some units. In addition, some mudstone beds contain sparsely distributed 1%-5% brachipod shells (depth

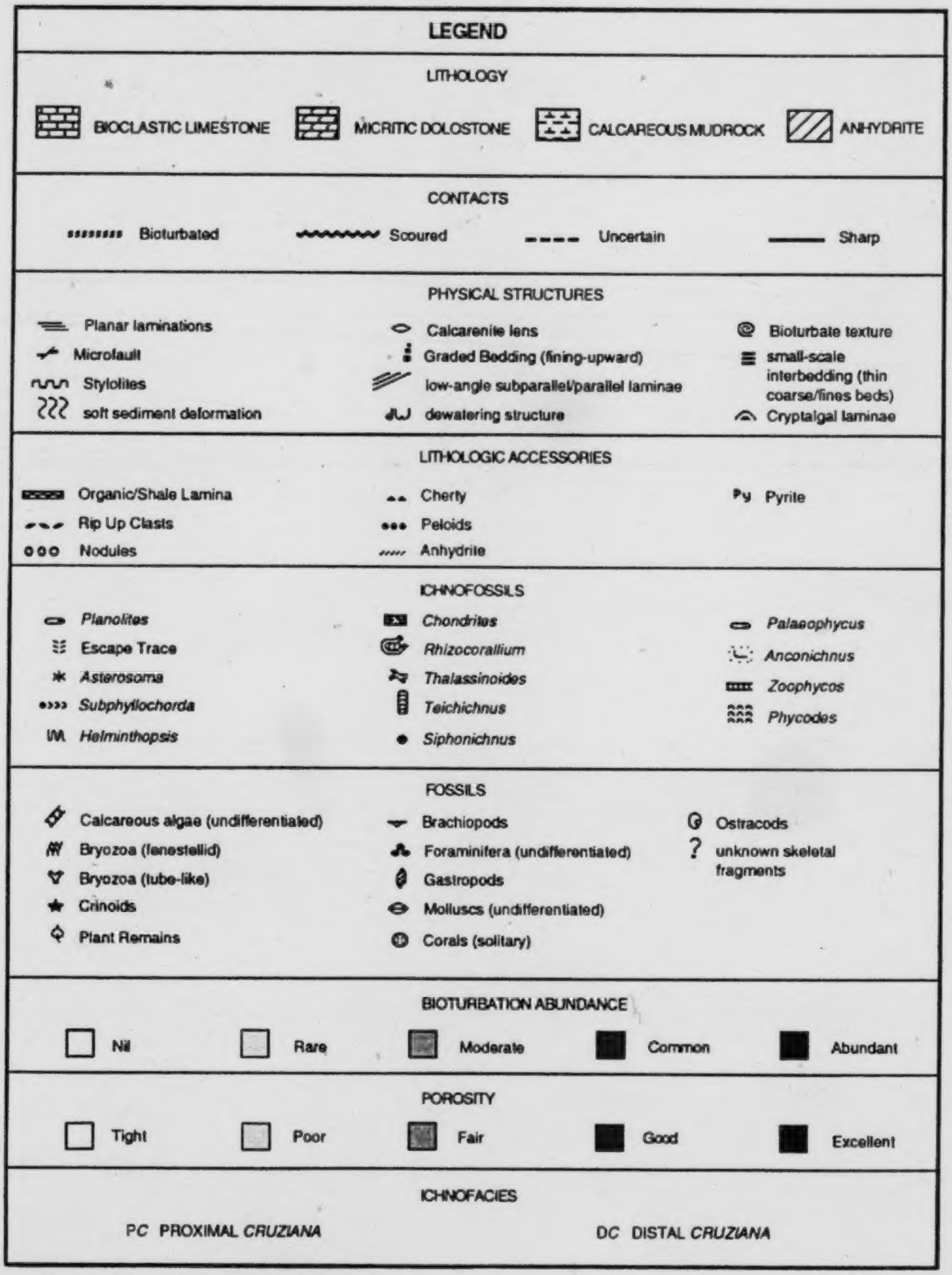
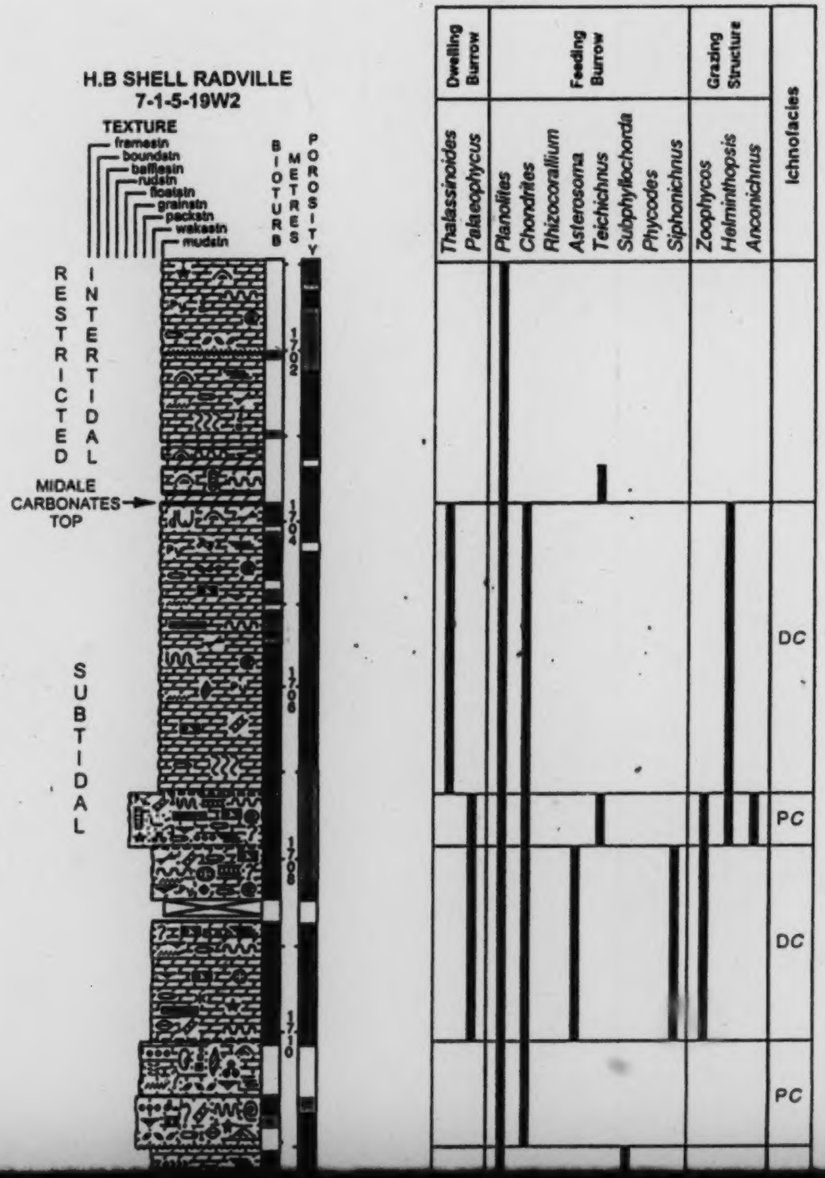


Figure 3. Symbols for litholog in Figure 4.


H.B SHELL RADVILLE
7-1-5-19W2
TEXTURE
framestn
boundstn
bafflestn
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BIOTURB
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1702
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1708
1710
RESTRICTED
INTERTIDAL
MIDALE CARBONATES TOP
SUBTIDAL
Dwelling Burrow
Thalassinoides
Palaeophycus
Feeding Burrow
Planolites
Chondrites
Rhizocorallium
Asterosoma
Teichichnus
Subphyllochorda
Phycodes
Siphonichnus
Grazing Structure
Zoophycos
Helminthopsis
Anconichnus
Ichnofacies
DC
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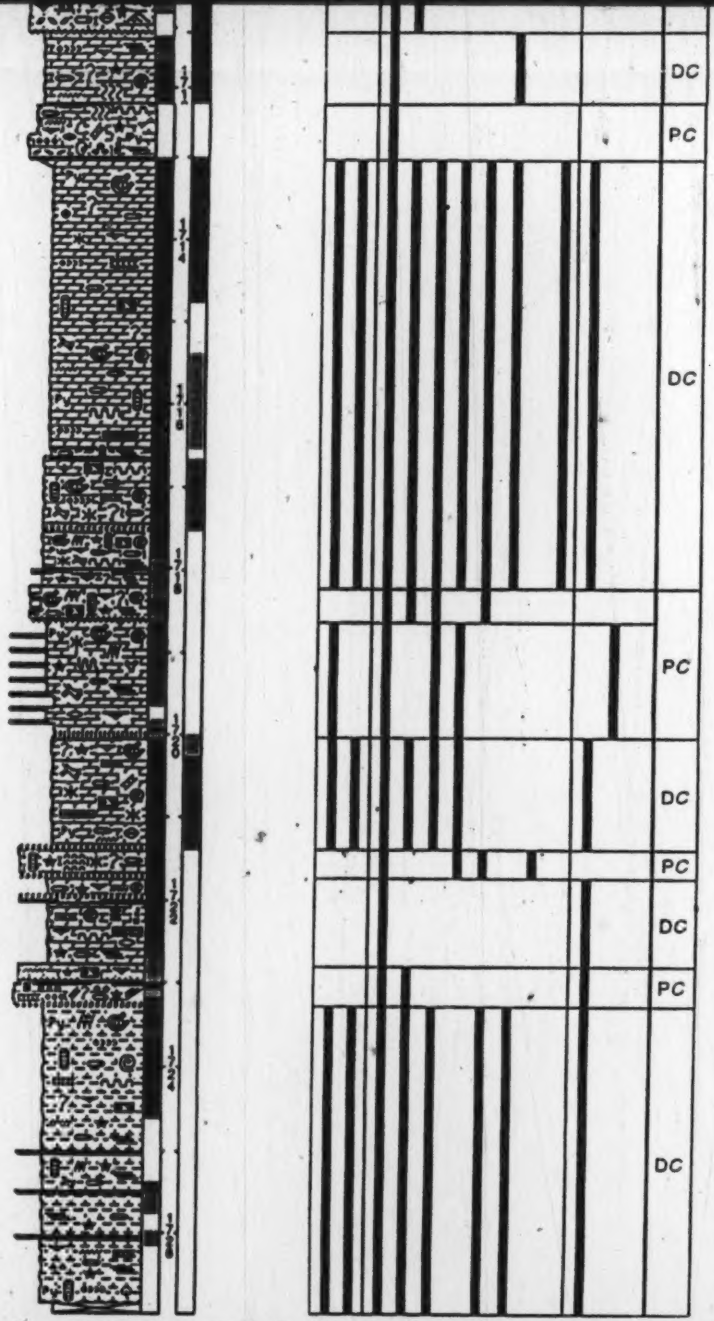

Figure 4. Litholog and Ichnology Table for the Midale Carbonates in well 7-1-5-19W2.

Ichnogenus	Ethology	Trophic Group	Probable Producer
Anconichnus	pascichnia	grazer	annelid*
Asterosoma	fodinichnia	deposit-feeder	annelid*
Chondrites	fodinichnia	deposit-feeder	sipunculid
Helminthopsis	pascichnia	grazer	annelid*
Paleophycus	domichnia	carnivore	annelid*
Phycodes	fodinichnia	deposit-feeder	annelid*
Planolites	fodinichnia	deposit-feeder	annelid*
Rhizocorallium	fodinichnia	deposit-feeder	crustacean
Siphonichnus	domichnia	deposit-feeder	bivalve
Subphyllochorda	fodinichnia	deposit-feeder	echinoderm (heart urchin)
Teichichnus	fodinichnia	deposit-feeder	annelid*
Thalassinoides	fodinichnia	deposit-feeder	crustacean
Zoophycos	pascichnia	grazer	nematode

Table 1. Ethological category, tropic group and probable producer of ichnogenera found in the Midale carbonate cores (* or other worm-like phyla).

1714.32 m and 1716.08 m). Most mudstone units contain 2%-5% unknown, fine-grained skeletal fragments and 1%-3% siliciclastic silt. Siliciclastic sediments form the coarse basal component of millimetre-scale, fining-upward laminae within the uppermost mudstone facies (depth 1701.49 m to 1702.88 m). The laminae, that contain minor amounts of organics and incipient stylolites define planar and wavy cryptalgal structures within the uppermost dolomudstone facies. Anhydrite-filled microfractures and replacive anhydrites are scattered throughout this facies. Upper cryptalgal-laminated dolomudstones lack bioturbation.

The underlying dolomudstones show a variety of bioturbate textures, ranging from slightly mottled to almost complete biogenic homogenization. A moderately diverse trace-fossil assemblage characterizes the lower and middle mudstone facies. A less diverse suite occurs in the upper mudstone facies, below the cryptalgal zone. The thick, thoroughly burrowed dolomudstone at 1716.08 m shows almost complete dolomitization of micrite (85%-90%). Other diagenetic features include incipient stylolites, minor silcification, and calcite recrystallization of shells (3%-5%).

Skeletal dolowackestone facies contain poorly sorted, medium to coarse grained allochems in a dolomitized micrite matrix. These textures are modified by variable degrees of bioturbation. In some sections, almost complete homogenization produced a bioturbate texture. In others, depositional laminae are locally visible, suggesting bioturbation has had less influence on texture. The degree of bioturbation varies from common to abundant in the dolowackestone facies and a moderately diverse ichnofossil suite is typical.

Skeletal material in the dolowackestone facies includes shell fragments and large, whole brachiopods. Grain size ranges from less than one millimetre to centimetre scale. Coarser skeletal wackestones are commonly poorly sorted and have a wide size range. This contrasts with finer-grained skeletal wackestones which commonly are moderately to well sorted. Dolomicrite constitutes 65%-75% of the composition of this facies. Skeletal components include 5%-15% brachiopod, 5%-15% unknown skeletons, 2%-5% crinoids, and 3%-5% organics (opaques). Some braciopod fragments at 1717.38 m display evidence of bioerosion (algal borings). The skeletal constituents in this facies are mostly undolomitized. The surrounding micrite matrix shows complete to patchy dolomitization (depth 1717.38 m).

The skeletal wackestone facies is restricted to the lowest portions of the core. The average size of allochems in this facies is medium-grained though parts of the unit contain fine and coarse components. Although the micritic matrix is partially dolomitized, its quantity and distribution is patchy and variable. Total amounts of bioturbate textures increase upward. Other parts of this facies are devoid of biogenic structures. These undisturbed sections commonly show planar laminae. In other sections of the core, the skeletal wackestones show little evidence of bioturbation, displaying only rare mottled to wave laminated fabrics. The bulk constituents of this facies consist of 75%-85% micrite, 5%-10% unknown skeletal fragments, 1%-5% brachipod, 2%-5% crinoid, 2%-3% opaques (organics) and 1% siliciclastic grains.

Parts of the skeletal wackestone facies (1721.76 m) contain a greater volume of skeletal components. These grain-rich wackestones are composed of 45%-50% micrite, 10%-15% brachiopod, 20% crinoid, 10% unknown skeletal fragments, 1%-2% calcareous algae, 1%-2% bryozoans, and 1% opaques (organics). These beds are generally coarse grained, and their components float in micrite matrix. Diagenetic features include rare dolomitization of micrite and selective dolomitization of burrows.

BIOCLASTIC FACIES ASSOCIATION

The bioclastic facies association is characterized by textural relationships that consist of peloidal-skeletal grainstones and peloidal-skeletal packstones. These textural relationships are composed of fine-to coarse-sized, whole shells, skeletal fragments and peloids. Such components show poor to moderate sorting of allochems and a variety of grain-to-grain contacts. Peloids are the major constituent of this facies and comprise up to 50% of the rock. Skeletal components of the peloidal-skeletal grainstones contain 5%-15% brachipod skeletons and fragments. The skeletal-peloidal packstones contain 2%-5% brachiopod material. Crinoid content usually varies between 5%-20% and averages 10% within this facies. Other skeletal material include foraminifera, calcareous algae, ostracods and undifferentiated debris ('unknown skeletal fragments' on striplog).

This facies association contains an average of 10% intraclasts. Intraclasts range from 5%-20% of the bioclastic facies. Some bioclastic units show scoured (erosive) basal contacts which are demarcated by sharp-to-undulatory surfaces and are locally associated with intraclasts. Some bioclastic facies show well-defined graded bedding comprised of intraclastic, coarse, shelly and peloidal basal beds which grade up to finer-sized skeletal-peloidal packstone. Some bioclastic units have uncertain and bioturbated contacts with overlying and underlying units of the muddy facies association. The bioclastic facies at 1710.53 m and 1712.82 m show geopetal fabric and shelter porosity. The peloidal-skeletal packstone unit at depth 1710.32 m contains 20%-25% micrite. Generally, the micrite volume is lesser in other peloidal-skeletal packstone units.

Diagenetic aspects of the bioclastic facies association include spar cement (up to 25% of the rock), syntaxial overgrowths around crinoid ossicles, few micrite envelopes around foraminifera, and partial silicification of some brachiopod material (2%-3% volume of rock). Very little dolomitization (1%) has occurred in this facies. The peloidal-skeletal grainstone unit at 1723.08 m showed selective dolomitization of a possible *Thalassinoides* burrow. Two examples of peloidal-skeletal grainstone units which showed many of these diagenetic features, occur at 1712.82 m and 1710.53 m. Minor silica and dolomite, syntaxial overgrowths, some micritization, minor stylolitization, as well as equant and bladed spar characterize the diagenetic aspects of these fining-upward, bioclastic units.

TRACE FOSSIL SUITES

The distribution and associations of trace fossils in the Midale Beds are characteristic of two assemblages: 1) a distal *Cruziana* assemblage and 2) a proximal *Cruziana* assemblage. These ichnofacies recur cyclically in a vertically stacked pattern (Figures 3 and 4).

DISTAL *CRUZIANA* ASSEMBLAGE

Sediments of the muddy facies association display a moderately-diverse suite of ichnofossils are consistent with a distal *Cruziana* ichnofacies. They include *Planolites* (Figures 5A, 5B, 5C and 6A), *Chondrites* (Figures 5A and 5B), *Rhizocorallium* (Figures 5D and 6C), *Teichichnus* (Figures 5C, 6B and 6C), *Thalassinoids* (Figures 5A and 5C), *Asterosoma* (Figures 5A and 6A), *Zoophycos* (Figures 5A, 6B and 6D), *Helminthopsis* (Figures 5D and 7D), *Subphyllochorda* (Figures 5B and 6C), *Palaeophycus* (Figures 5B and 5C), and rare *Siphonichnus* (Figure 6D). Deposit-feeding structures are predominant in this assemblage. Representatives of dwelling and grazing structures also occur as significant elements. Dwelling structures are more common in the lower and middle parts of the succession. The grazing burrows *Zoophycos* and *Helminthopsis* are distributed more evenly throughout the succession.

Figure 5. Ichnologic features of the muddy facies association in core 7-1-5-19W2: (A) *Thalassinoides* (T), *Planolites* (P), *Asterosoma* (As), *Chondrites* (Ch), *Subphyllochorda*, depth 1717.50 m. (B) *Thalassinoides, Chondrites* (Ch), *Palaeophycus* (Pa), *Planolites* (P), *Zoophycos, Subphyllochorda* (Su), depth 1716.35 m. (C) *Thalassinoides* (T), *Planolites* (P), *Palaeophycus* (Pa), *Chondrites, Teichichnus* (Te), *Subphyllochorda*, depth 1715.71 m. (D) *Planolites, Asterosoma, Rhizocorallium* (Rh), *Helminthopsis* (H), depth 1718.74 m.

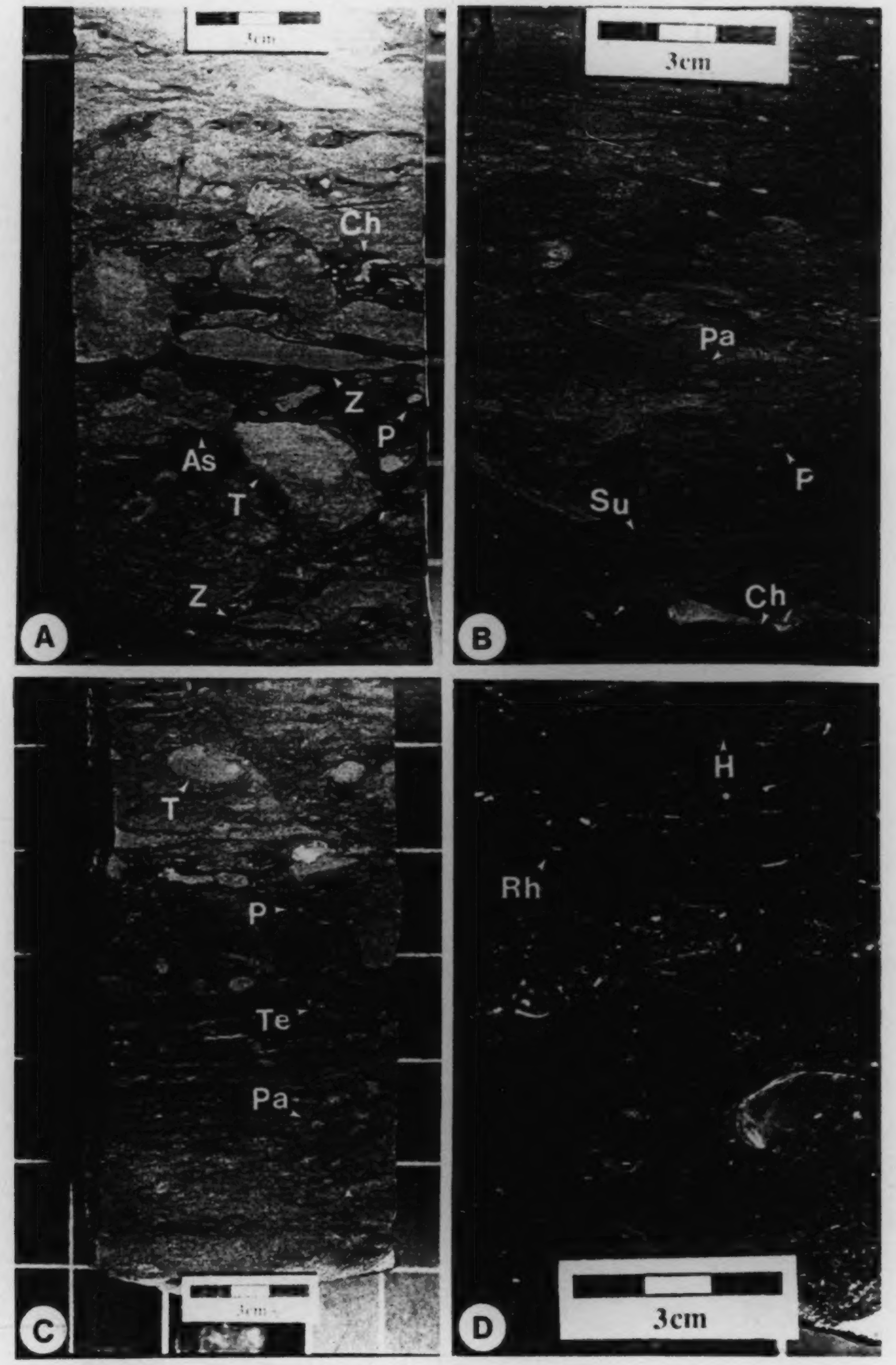
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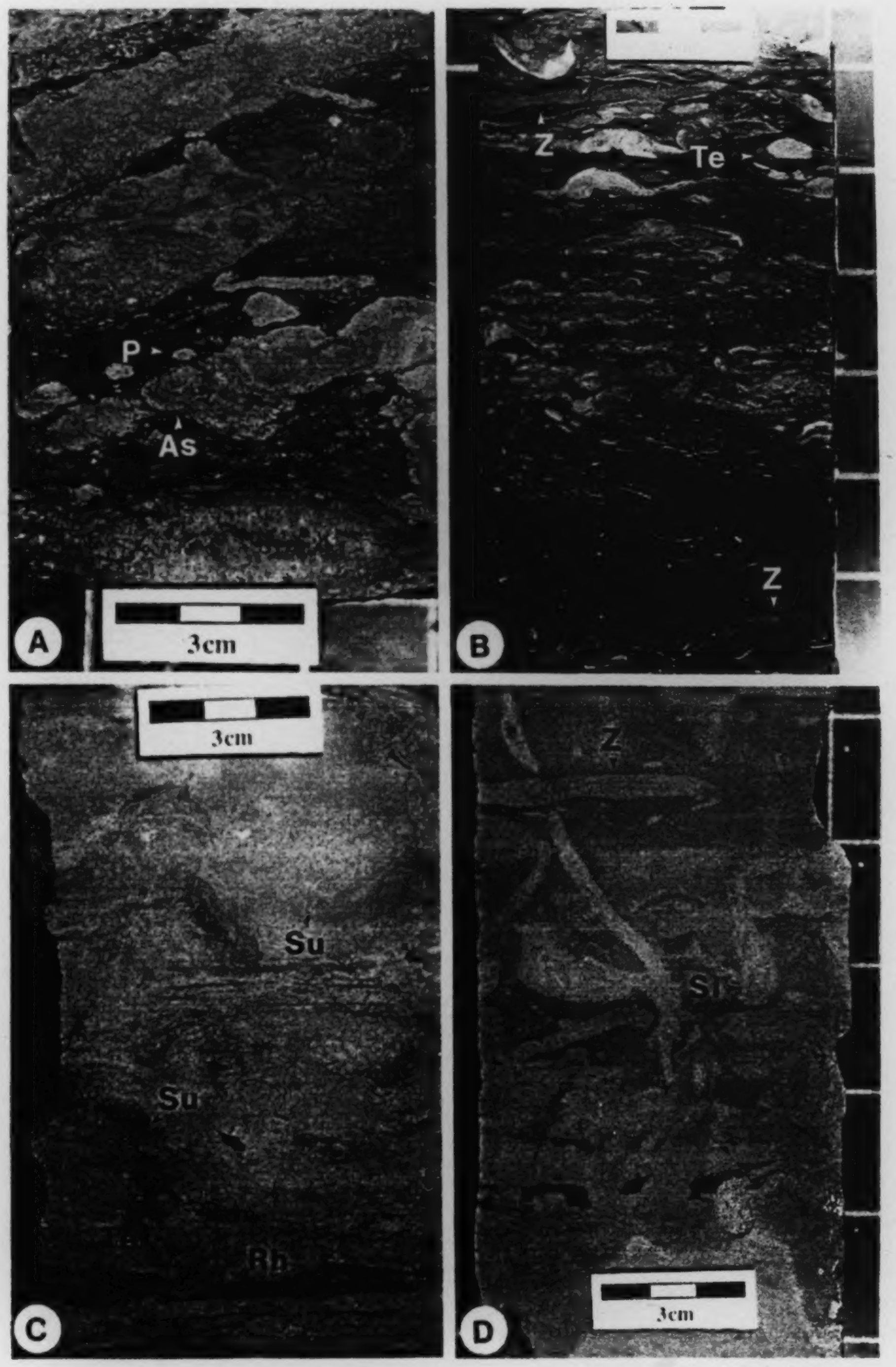
Figure 6. Ichnologic features of the muddy facies association in core 7-1-5-19W2: (A) *Asterosoma* (As), *Planolites* (P), depth 1721.15 m. (B) *Planolites, Chondrites, Teichichnus* (Te), *Zoophycos* (Z), depth 1717.81 m. (C) *Planolites, Rhizocorallium* (Rh), *Teichichnus* (Te), *Subphyllochorda* (Su), depth 1717.29 m. (D) *Zoophycos* (Z), *Siphonichnus* (Si), depth 1713.88 m.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PROXIMAL *CRUZIANA* ASSEMBLAGE

The coarse-grained, bioclastic facies association displays a proximal *Cruziana* ichnofossil suite. This suite comprises *Planolites, Chondrites* (Figure 7B), fewer *Teichichnus, Asterosoma, Rhizocorallium,* and *Palaeophycus* (Figure 7D), and rare *Anconichnus, Helminthopsis, Zoophycos* (Figure 7D), and *Phycodes*. Escape traces (fugichnia) are locally associated with the bioclastic facies association (Figure 7A). This assemblage is less diverse than the distal *Cruziana* suite and overall bioturbation is significantly reduced or absent. This ichnofossil suite is dominated by deposit-feeding structures. Dwelling structures such as *Palaeophycus* are less common. Grazing structures such as *Anconichnus, Helminthopsis* and *Zoophycos* are rare. *Planolites, Chondrites,* and fewer *Teichichnus* are the most common ichnogenera associated with the bioclastic facies association.

INTERPRETATION

The muddy and bioclastic facies associations described above, form a distinct vertical stacking pattern characterized by an alternation from a muddy to bioclastic units (Figures 3 and 4). Stacking patterns and sedimentologic features suggest a subtidal, storm-influenced, marine succession culminating in restricted intertidal deposits near the top of the Midale Beds (Figure 8A). The uppermost dolomudstone unit is interpreted to represent the shallowest environment in the Midale carbonates.

Environmental turnover from subtidal to restricted intertidal environments occurs at 1703.7 m at the top of the Midale Beds (Figure 8A). This is demarcated by an abrupt decrease in bioturbation, the presence of cryptalgal laminae, intraclasts and desiccation cracks associated with subaerial exposure surfaces (Figure 8). The millimetre scale, fining-upward cycles (cryptalgal laminites) within the uppermost dolomudstone facies are

Figure 7. Sedimentologic and ichnologic characteristics of the bioclastic facies association in core 7-1-5-19W2: (A) Storm bed showing fining-upward bioclastic unit, basal coarse-grained, shell-lag, combined-flow ripples, escape trace (f), depth 1710.58 m. (B) Storm bed showing fining-upward bioclastic unit, *Chondrites* (Ch) in muddy intraclast, combined-flow ripples, fracture filled with crystalline anhydrite, depth 1712.70 m. (C) Bioclastic unit exhibits well-preserved combined-flow ripples, soft sediment deformation, depth 1711.18 m. (D) Upper part of bioclastic facies at depth 1707.41 m, trace fossils present include *Zoophycos* (Z), *Helminthopsis* (H), *Anconichnus* (An), and *Palaeophycus* (Pa).

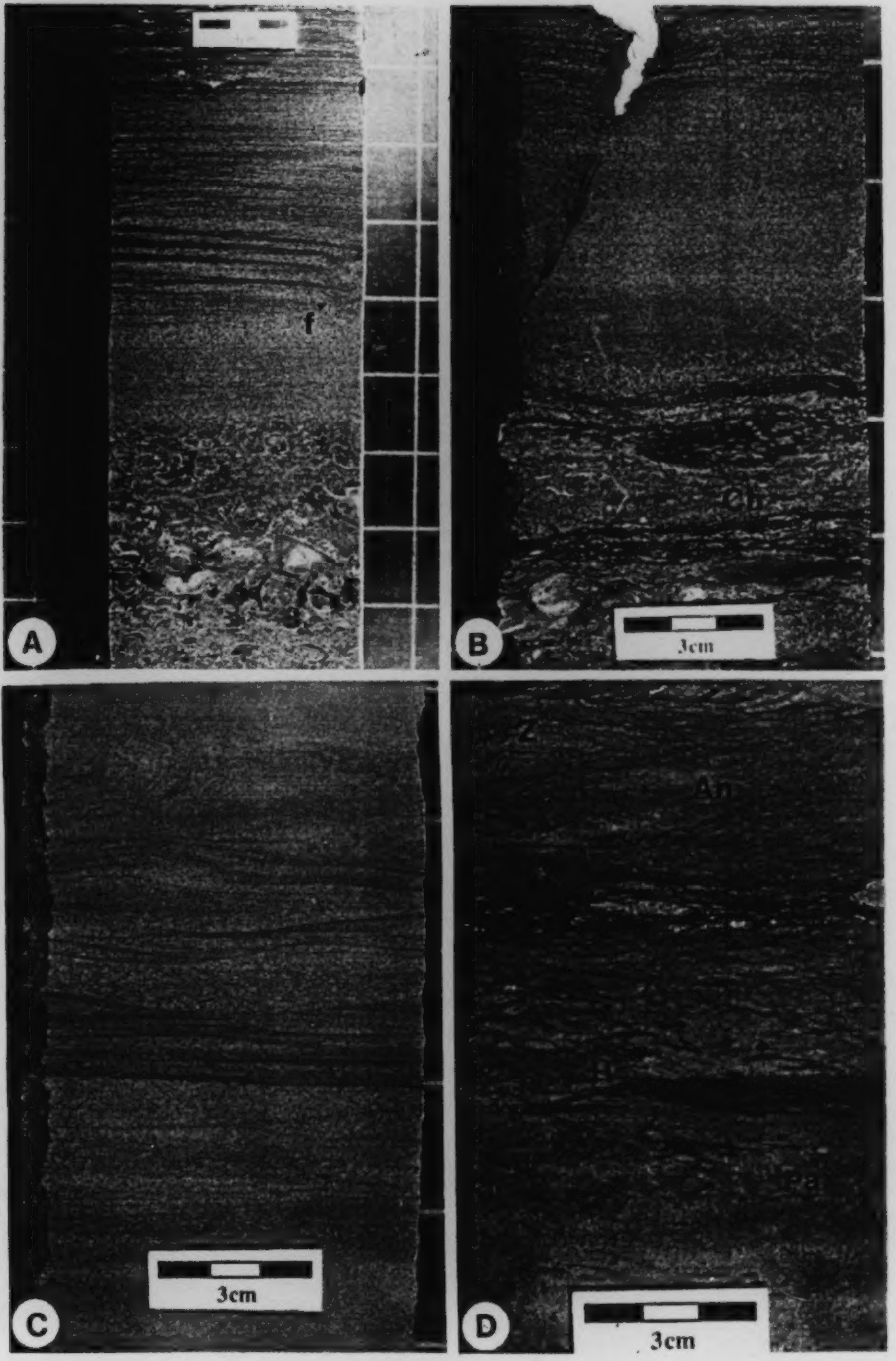
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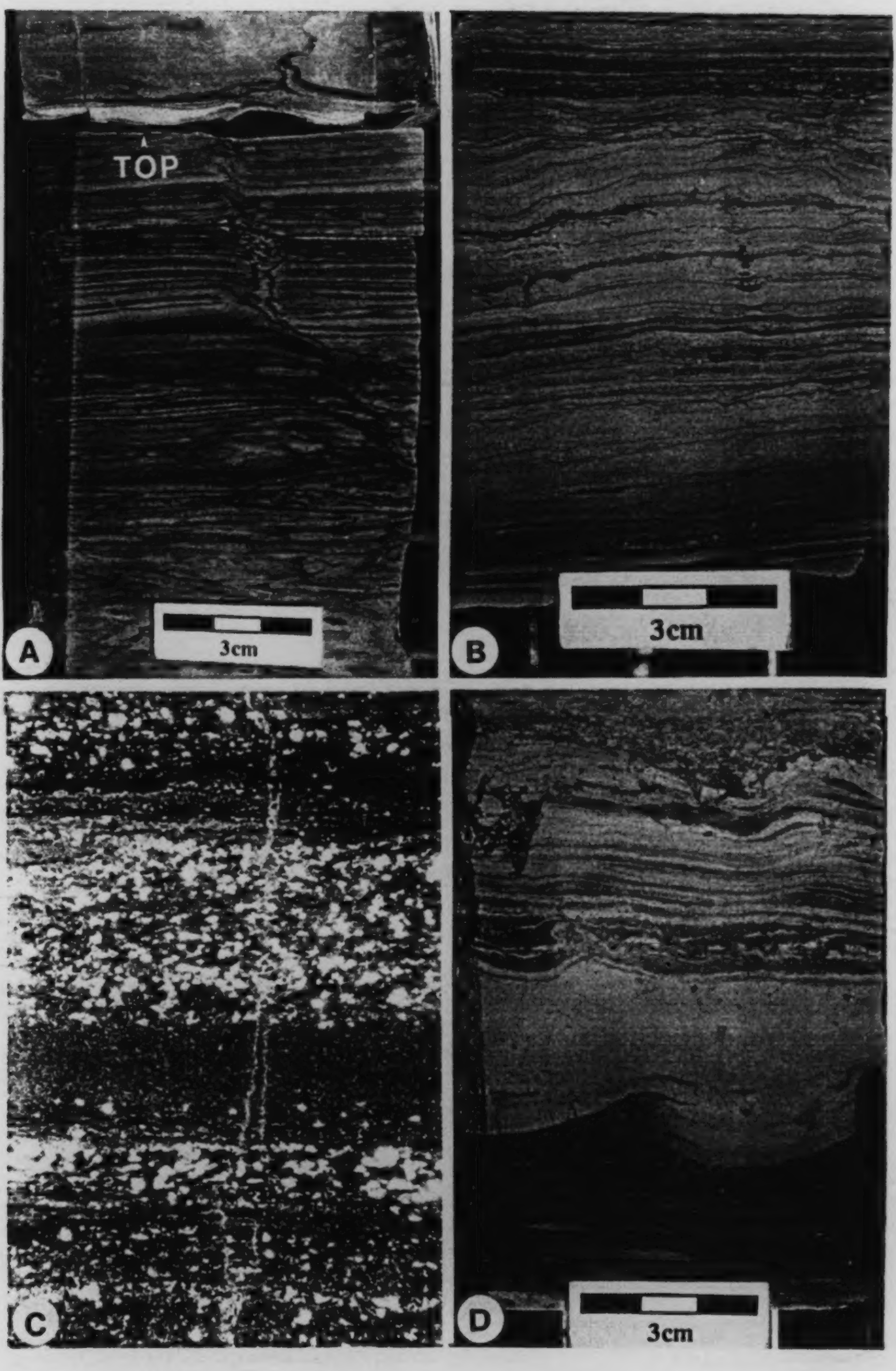
Figure 8. Sedimentologic characteristics of the restricted intertidal deposits in core 7-1-5-19W2: (A) Midale top at base of bedded anhydrite at depth 1703.7 m, cryptalgal laminae reflects onset of restricted intertidal conditions, dewatering structure. (B) Cryptalgal laminae in dolomudstone at depth 1700.01 m. (C) Photomicrograph of dolomudstone at depth 1702.88m, note lack of bioturbation and preservation of millimetre-scale, silt-based, fining-upward cycles (storm beds), stylolitization, organics (opaque), field of view is 2.5 mm wide. (D) Erosive subaerial exposure surface with associated desiccation cracks and rip-up clasts, depth 1695.53 m.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interpreted to be the result of supratidal/intertidal sedimentation during storms (Ginsburg and Hardie, 1975; Hardie and Shinn, 1986).

Cyclic facies relationships, relative thicknesses of muddy rock units, and the predominance of deposit-feeding biogenic sedimentary structures indicate that deposition was in a generally quiet-water environment which was episodically influenced by more energetic flow regimes. Episodic sedimentation resulted in stacked coarsening-upward cycles. The relatively thinner, coarse-grained bioclastic beds are sandwiched by thicker, burrowed units of the muddy facies association. Units of the muddy facies association are interpreted as ambient fairweather sediments and those of the bioclastic facies association as storm-introduced shallow shelf sediments. The relatively thick muddy facies association is the product of slow, fairweather deposition. This low-energy sedimentation was punctuated by high-energy flow regimes which resulted in rapid influx, minor erosion and deposition of coarse bioclastic sediments in an otherwise quiet-water environment. Combined-flow ripples and low-angle, parallel/subparallel laminae ("quasi-parallel laminae" of Arnott, 1993) in some bioclastic beds support this interpretation. It is interpreted that deposition of the Radville area Midale carbonates occurred in the deeper-subtidal, outer-to-inner shelf environment of Kent's (1987a; 1988) depositional model.

Biotic diversity within the bioclastic facies association is shown by skeletons of crinoid, brachiopod, bryozoans, calcareous algae, gastropod, mollusks, solitary corals, ostracods, and foraminifera suggest a normal marine, shallow-subtidal source for these bioclasts (Flugel, 1982). This is further supported by algal borings in brachipod shells. Similar skeletal components within the small and larger scale interbedded bioclastic units suggest that storm-induced basinward transport, deposition and subsequent biogenic reworking are responsible for introduction and incorporation of shallow-water sediments within muddy units. Many of the skeletal dolowackestone units were probably derived from biogenic mixing of thinner interbedded units of the muddy and bioclastic facies. This is demonstrated by rare preservation of small scale interbeds in some parts of the skeletal dolowackestones.

In the core of Midale carbonates from well 7-1-5-19W2, storm action is indicated by both the sedimentologic and ichnologic aspects of bioclastic units. Some bioclastic units show sharp or scoured bases which are locally associated with intraclasts or shell lags. Geopetal structures and shelter porosity characterize some of the thicker coarse-grained lags. These lags form the basal components of centimetre-scale fining-upward cycles. Upper parts of some cycles are characterized by combined-flow ripples, low-angle to parallel-subparallel laminae and bioturbated upper contacts. Ichnologic evidence includes rare escape structures and probable opportunistic behaviours/colonization by endobenthos. Many similar features have been described from other ancient and modern carbonate and siliciclastic tempestites (Kreisa and Bambach, 1982; Aigner, 1985; Pemberton *et al.*, 1992, MacEachern and Pemberton, 1992; Frey and Goldring, 1992; Walker and Plint, 1992).

The diversity and abundance of trace fossils are indicative of fully marine, deeper-subtidal environments. Diversity of trace fossil assemblages in the Midale carbonates of the Radville area, are represented by the occurrence of various ethologic classes of traces including dwelling burrows, feeding burrows, escape traces and grazing structures (Table 1).

The trace fossils are representative of two assemblages: distal *Cruziana* and proximal *Cruziana* ichnofacies. The cyclic distribution of these two ichnofacies, reflect the behavior of endobenthic organisms in response to shifts in environmental parameters which are induced in part, by changes in physical and/or chemical processes operating within the environment. Since the oscillations in ichnofacies are closely associated with textural facies, it is reasonable to postulate that the shifts in environmental parameters were induced by the storm processes which influenced the Midale shelf.

Between storm events, the substrates of the muddy facies association were exploited by a variety of endobenthos that used predominantly deposit-feeding strategies as well as created some dwelling and grazing structures (Vossler and Pemberton, 1989; Bromley, 1990). Since the greatest abundance and diversity of trace fossils occur in the distal *Cruziana* ichnofacies, the stable, muddy environments are considered to represent optimal conditions for colonization (Ekdale *et al.*, 1984; Bromley, 1990). Parts of the muddy facies association show almost complete biogenic homogenization. Discrete traces are difficult to recognize in these intensely bioturbated sediments. This bioturbate texture clearly indicates a high rate of biogenic reworking (Wheatcroft, 1990; Bromley, 1990).

Traces of the distal *Cruziana* assemblage, particularly the grazing and deposit-feeding structures such as *Zoophycos, Subphyllochorda, Helminthopsis, Rhizocorallium, Teichichnus,* and *Asterosoma* indicate outer-to-inner shelf, deeper subtidal environments (Seilacher, 1967; Wetzel and Werner, 1981; Smith and Crimes, 1983; Ekdale *et al.*, 1984; Kent, 1987a; Kent *et al.*, 1988; Vossler and Pemberton, 1989; Bromley, 1990). The abundance and diversity of this assemblage is consistent with the normal marine interpretation based on body fossils for the Midale carbonates in well 7-1-5-19W2.

Deep-penetration burrows, such as *Chondrites* and *Zoophycos*, are abundant locally in the muddy facies association. These deposit-feeding and grazing structures are indicative of trace-makers taking advantage of plentiful organic food resources and stable conditions typical of offshore, shelf areas (Vossler and Pemberton, 1989). In thin sections of muddy units organic material appears opaque. The presence of minor pyrite is indicative of local, oxygen-poor, reducing conditions which probably resulted from decaying organic matter (Vossler and Pemberton, 1989). This suggests the trace-making organisms of *Zoophycos* and *Chondrites* were capable of downward penetration into buried sediments in search of food and were tolerant of local dysaerobic conditions (Vossler and Pemberton, 1988; 1989).

Since *Chondrites, Zoophycos* and *Thalassinoides* are traces of deep burrowers which typically colonized the muddy facies association, it is interpreted that downward penetration from higher levels explain their presence in the upper parts of the bioclastic facies association at 1707.3 m and 1719.5 m (Ekdale *et al.*, 1984, Bromley, 1990; Frey and Goldring, 1992). The trace-makers likely attempted to exploit buried food resources in rapidly deposited, storm beds.

DISCUSSION

Storm processes are one of the most important mechanisms of carbonate sedimentation in both modern and ancient shelf environments (Aigner, 1985). In modern environments, massive volumes of shallow-water carbonate sediments are mobilized and transported from the subtidal carbonate factory by storm action (Hubbard, 1992). Similar processes have also been recorded in many ancient carbonate depositional settings (Kreisa and Bambach, 1982; James, 1984; Handford, 1986; Sami and Desrochers, 1992; Jones and Desrochers, 1992; Dixon and Graf, 1992; Lavoie, 1992; Lee and Kim, 1992; Jennette and Pryor, 1993). The number of recent publications on storm deposits in carbonate depositional environments reflect the importance of this mechanism of sediment transport and deposition. Walker and Plint (1992) documented similar processes in siliciclastic, shallow marine environments.

Ichnologic aspects of tempestites have been discussed in detail (Pemberton and Frey, 1984; Vossler and Pemberton, 1988, 1989; MacEachern and Pemberton, 1992; Frey and Goldring, 1992; Pemberton *et al.*, 1992; Pemberton and MacEachern, 1997). Consequences of episodic storm events on the outer-to-inner shelf environment include the following effects on the bioclastic facies: (1) sedimentary characteristics which reflect initial, main and waning stages of storm events; (2) redistribution of allochems, organics and siliciclastics; and (3) ecologic changes such as food resources/supply, or substrate conditions for a biologically significant duration (Pemberton *et al.*, 1992). These effects are manifest in both the sedimentologic and ichnologic character of the bioclastic facies association.

The proximal *Cruziana* ichnofacies is associated with the bioclastic rock units which are interpreted as storm beds. Therefore, the inherent ichnological characteristics of these beds represent behaviors induced by periodic, high-energy conditions in an otherwise stable, low-energy environment. Trace-makers which colonized bioclastic substrates probably were opportunists (Pemberton and Frey; 1984; Vossler and Pemberton, 1989; Pemberton *et al.*, 1992; MacEachern and Pemberton, 1992; Frey and Goldring, 1992; Pemberton and MacEachern, 1997).

Bromley (1990) defined opportunistic strategy as rapid colonization of vacant niches. Pemberton *et al.* (1992) outlined the mechanisms of opportunistic colonization. Opportunistic trophic strategy exhibited by trace fossils refer to feeding behaviors in unexploited niches, usually associated with physiologically stressful conditions (Bromley, 1990; Pemberton *et al.*, 1992). Storm events produce unexploited niches by rapidly depositing shallow shelf sediments (allochems) and organics in outer-to-inner shelf areas under the influence of flow regimes which contrast that of fairweather (background) sedimentation.

Punctuation of quiescent periods by energetic storm events result in local erosion, rapid deposition, burial of shallow shelf bioclasts and organic material, and intercalation of facies as fairweather sedimentation is resumed. Wheatcroft (1990), and Frey and Goldring (1992) discussed factors which influence preservation potential of biogenic sedimentary structures in environments characterized by episodic sedimentation. The buried organics and organic-coated sediments are the food resources that opportunistic endobenthos seek to exploit. Rapid burial may cause death and therefore, defaunation of some endobenthos by suffocation, thereby, further increasing the organic content of tempestites and upper parts of underlying units (Vossler and Pemberton, 1989). Thus reduction in trace fossil diversity in storm-generated units may be indicative of partial defaunation as well as opportunism by surviving organisms.

Ichnologic evidence of opportunistic colonization of storm-generated, bioclastic substrates in the Midale carbonates includes *Anconichnus, Chondrites, Palaeophycus, Planolites,* and *Rhizocorallium*. These trace fossils are common to rare in the less diverse, proximal *Cruziana* ichnofacies and tend to occur in zones within the bioclastic facies association. *Planolites* and *Chondrites* are ubiquitous within the bioclastic facies association. Trace-makers of deep and shallow deposit-feeding burrows and grazing structures have been interpreted to be opportunistic animals which attempted to exploit storm-buried food resources (*cf.* Vossler and Pemberton, 1988; Raychaudhuri and Pemberton, 1992).

Although bioturbate texture is apparent in most of the Midale carbonates of the Radville area, the upper bioclastic and muddy facies show minimal to no bioturbation. The scarcity of traces in these parts of the succession reflects ecological stresses which made colonization of these substrates difficult to achieve by endobenthic organisms. The bioclastic facies probably represents unstable substrates, high-energy and stressful environments characterized by erosion and rapid deposition. These conditions are reflected by the coarse grain-size of allochems, poor sorting, scoured bases and intraclasts within the thicker, bioclastic beds.

In the uppermost dolomudstone facies, chemical stress (hypersalinity) is indicated by paucity of body and trace fossils, cryptalgal laminites and bedded anhydrite. Exclusion of organisms and consequent bioturbation in this restricted intertidal environment has allowed preservation of storm-generated, cryptalgal laminites. These two examples illustrate some of the ecologic controls on colonization of substrates by various organisms. Within subtidal units of the Midale carbonate succession, variations in bioturbate texture (abundance of bioturbation on striplog) are coincident with facies variations. This also reflects organisms response to the episodicity of bioclastic sedimentation on the outer-to-inner Midale shelf.

The recognition of trace fossils and their emplacement in an ichnofacies framework are useful in determining subtle, but important changes in ecologic niches of soft-bodied organisms by storm sedimentation on outer-to-inner carbonate shelf environments. The impact of storms on a carbonate shelf are probably related to proximality of shorelines (Sami and Desrochers, 1992; Lee and Kim, 1992). The subtle environmental changes would have been difficult to identify, merely through conventional sedimentologic analysis.

Several sedimentologic trends are apparent in the Midale carbonates of the Radville area. Although Mississippian carbonates in the Williston Basin were deposited during transgressive episodes, the Midale succession in the Radville area shows overall upward shallowing from deeper-subtidal to restricted intertidal environments (Lake, 1991). This regressive-upward trend likely occurred as a result of basin infilling and progradation of the intertidal sabkha succession. The bioclastic facies association shows thickening and coarsening-upward trends. The trends of these storm-generated units reflect increasing proximality (MacEachern and Pemberton, 1992; Sami and Desrochers, 1992; Lee and Kim, 1992; Raychaudhuri and Pemberton, 1992).

CONCLUSIONS

(1) Two textural facies associations and ichnofossil suites are identified in the Midale carbonates of the Radville area. The distal *Cruziana* ichnofacies occur in the muddy facies association. The proximal *Cruziana* ichnofacies occur in the bioclastic facies association. The muddy facies association is interpreted as a fairweather deposit and the bioclastic facies association as storm beds. The cyclicity, thickness and composition of allochems of bioclastic beds indicate episodic, high-energy, influxes of shallow-water carbonate sediments into a low-energy, deep-subtidal, outer-to-inner-shelf environment. The succession shows a shallowing-upward trend which culminates in restricted intertidal deposition near the top of the Midale carbonates.

(2) Ichnofossils are an integral part of the Midale carbonate succession and provide a greater understanding of the nature of storm sedimentation and related ecological changes. Subtle shifts in environmental parameters were only apparent through ichnologic interpretation which supplemented conventional sedimentologic analysis.

(3) More ichnologic and sedimentologic research is required to understand the processes and patterns of carbonate sedimentation in the Mississippian sequence of the Williston Basin, particularly the nature of episodic sedimentation, its impact on endobenthos and bioturbation, and the effects of bioturbation on diagenesis and reservoir distribution.

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CHAPTER 3

A CRITIQUE OF THE ICHNOFABRIC CONCEPT: LIMITATIONS IN TERMINOLOGIES, CLASSIFICATIONS AND APPLICATIONS

INTRODUCTION

The physical and morphological characteristics of textures generated through bioturbation define both discrete ichnofossils and local indiscrete sedimentological heterogeneities, which record manifestations of specific organismal behaviours in substrates (Seilacher, 1967 a,b; Byers 1982; Ekdale *et al.*, 1984; Bromley, 1990, 1996; Crimes and Droser, 1992). The paleoenvironmental and paleoecological significance of discrete trace fossils have been documented extensively in the ichnological literature. Seilacher (1953; 1957; 1964; 1967 a; 1978 a) introduced the ichnofacies concept, which provided a framework for understanding the nature and distribution patterns of recurring ichnofossil suites. This approach is focused on identifications of discrete trace fossils, documentations of associations, and mapping of suites in local and regional sedimentological frameworks (Seilacher, 1964; 1967 a; 1978 a). Such procedures provided data useful for interpretations of changes in behaviour manifested in substrates, and attributed these to responses induced by paleoenvironmental and paleoecological gradients (Seilacher, 1964, 1967, 1978 a; Frey *et al.*, 1990). The ichnofacies approach has been utilized effectively in understanding biotic processes, and in reconstructions of paleoenvironments. Since its initial publication, this concept has represented one of the cornerstones of modern ichnology.

Conversely, a more contentious issue in ichnological circles has been the question of how to systematically classify indiscrete products of bioturbation in a manner that rendered these descriptions useful for paleoecological interpretations, and in paleoenvironmental reconstructions. Consensus on the most appropriate approaches to classification has been elusive among ichnologists and sedimentologists. The principal reasons for these disagreements include: (1) utilizations of non-genetic criteria for formulations of classifications, and (2) genetic applications of such schemes in reconstructions of paleoenvironments. To exchange ideas and explore for potential solutions to these problems, several international conferences on ichnofabrics were recently convened (Ekdale, 1992; Bromley, 1993). At these conferences, and in ichnological literature on bioturbate textures, debates have been focused mainly on two problems: (1) terminological inconsistencies, and (2) erections and applications of non-genetic classification schemes. Since productions of discrete trace fossils and indiscrete bioturbate textures have common origins in biotic interactions with substrates, a requisite for classifications of both these ichnological products is congruence in philosophical foundations.

TERMINOLOGICAL PROBLEMS

Ichnological literature is besieged with jargon and terminology inconsistencies (Frey, 1973; Ekdale and Pollard, 1991). This problem is likely the result of widespread misuse of terms, and inventions of new ones *in vacuo* of genetic, historical, and linguistic contexts. Recently, debates on terminology problems resulted in controversy and vehement exchanges between trace fossil workers, on applications and relative significance of terms such as "bioturbate textures" and "ichnofabrics" (Frey and Pemberton, 1990, 1991; Ekdale *et al.*, 1991). This paper subscribes to the original terminology and fundamental definitions proposed in works that pioneered studies on indiscrete bioturbate textures (Richter, 1952; Schäfer, 1956; Reineck, 1963). In these studies, definitions of terms such as "bioturbation" and "bioturbate texture" referred to processes of organism-sediment interactions, and to modified textural relationships, respectively (Richter, 1952; Schäfer, 1956; Reineck, 1963).

A wide array of terms have been subsequently substituted for generic descriptors of both the products and processes of bioturbation. Such relatively liberal applications of ichnological terms has resulted in inconsistencies with regard to original definitions. Rampant misuse of specific terminologies has created some confusion in the literature. Selected examples of terms substituted for bioturbate textures include "bioturbites"

(Winder, 1968), "ichnofabrics" (Ekdale and Bromley, 1983; Ekdale *et al.*, 1984; Droser and Bottjer, 1986; Droser and Bottjer, 1987; 1988 a, b; 1989 a, b; 1990; 1993; Bottjer, 1987; Bottjer *et al.*, 1988, 1995; Bromley, 1990, 1996; Bottjer and Droser, 1991, 1992, 1994; Crimes and Droser, 1992; Droser, 1995; Droser *et al.*, 1996), "bio-retexturing," "vertical sediment bio-mixing," "pseudo-chickenwire texture," "bio-spoil beds," "pseudo-lamination" (Pedley, 1992), and "biofabrics" (Goldring and Jensen, 1996).

Alternatively, biotic processes which modified substrates have been dubbed commonly as "reworking," and in rare cases as "bioturbidation" Winder (1968). Sadly, the liberal use of terminology has reached the point of incoherence, where verbs have been substituted literally for nouns and *vice versa*.

To avoid problems derived from inconsistent applications of historically-significant ichnological terms, we call for slight modifications to some previous definitions, and proposes new ones (Tables 1 and 2). The proposed changes have been designed to distinguish clearly, differences between bioturbational processes and products. These modifications have striven to maintain the spirit of original definitions and linguistic integrity, and to preserve inherent sedimentological and biological connotations of specific terms such as "bioturbation," "bioturbate textures," and "ichnofabrics."

Bioturbation

Early definitions of "bioturbation" included all displacements of soft sediments and soil by the activities of animals (Richter, 1936; Hantzschel and Frey, 1978). However, this term has been misused commonly in both sedimentological and ichnological papers. This term is ill-used as a noun, contrary to the verb defined originally in the German literature (Richter, 1952). The English translation of this verb is consistent with requisites for its construction, including the word stems "bi" and "turb" which denoted "life" and "disturb," respectively (Kennedy, 1996), and addition of the suffix "-ation" to verbs in reference to actions (Oxford Dictionary, 1992, p. 477). Although this verb has been misused commonly as a noun in the literature, it was understood clearly from sentence contexts that authors had referred actually to bioturbate textures rather than biotic processes. To avoid

ORIGINAL DEFINITION	REFERENCE	THIS STUDY
Bioturbation: the churning and stirring of a sediment by organisms; term introduced by Richter (1952) for the processes of sediment-mixing activities by animals	Richter, 1952; Frey, 1973; Hantzschel and Frey, 1978; Bates and Jackson, 1980; Bromley, 1990, 1996	**Bioturbation:** all biological processes that comprised animal-sediment interactions in unconsolidated or firm substrates, which rendered bioturbate textures; a verb restricted for generic descriptions of biotic processes or activities that modified textural relationships in soft or firm substrates
Texture: the general physical appearance or character of a rock including the geometric aspects of, and the mutual relations among, its component particlesor crystals; e.g. the size, shape and arrangement of the constituent elements of a sedimentary rock	Bates and Jackson, 1980	**Carbonate Texture:** terms for modified Dunham's (1962) classes that refer to gross relationships among constituent elements of the rock (allochems, micrite, spar); typically, fabrics show effects of physiogenic, biogenic and diagenetic processes
Bioturbate Texture: gross texture imparted to sediments by extensive bioturbation; typically consists of dense, contorted, or interpenetrating burrows or other traces, few of which are distinct morphologically	Frey, 1973; Frey and Pemberton, 1985	**Bioturbate Texture:** biologically-produced gross relationships among substrate constituents that resulted from spatial arrangements of burrow fabrics; these consist of local heterogeneities defined by grain-size contrasts and alignments between fills and host substrates, and homogeneous affinities between such aspects, typically consist of one or more burrow fabrics
Burrow Mottled: where burrows are somewhat less crowded and are thus more distinct individually	Frey, 1973; Frey and Pemberton, 1985	**Burrow Mottled:** disturbed appearance of a rock due to biologically-produced textures and fabric-selective diagenetic alterations
Fabric: the orientation (or lack of it) in space of the elements (discrete particles, crystals, cement) of which a rock is composed	Bates and Jackson, 1980	**Fabric:** skeletal grain orientations or arrangements produced by physical sedimentary and diagenetic processes in carbonate deposits; i.e. allochem orientations which define laminae
Ichnofabric: all aspects of the texture and internal structure of a sediment that result from bioturbation and bioerosion at all scales; includes both bioturbation fabric and bioerosion fabric	Winder, 1968 Ekdale and Bromley, 1983; Ekdale *et al.* 1984; Droser and Bottjer, 1986; Bromley, 1990, 1996	**Ichnofabric:** biologically re-oriented and sorted substrate constituents which defined local heterogeneities that consisted of distinct or indistinct wall structures, and formed genetically-linked, structural aspects of bioturbate textures; generic descriptor for local arrangements defined by grain-size contrasts and alignments between fills and host substrates; synonomous to term"burrow fabric"
Cryptobioturbation: subtle, very-small-scale disruptions of grain fabrics throughout the laminae; thus otherwise distinct laminae commonly appears blurred; sediment can be totally reworked without actual obliteration of preexisting physical and biogenic sedimentary structures	Howard and Frey, 1975; Saunders *et al.*, 1994	**Cryptic Bioturbate Texture:** gross texture that result from in-situ biologically-rotated and locally displaced allochems that showed preservation of original sedimentary structures and fabrics; produced mostly by actions of microfauna and meiofauna

Table 1. Basic Definitions and Modified Terms Useful For Petrographic Study of Bioturbate Textures.

Table 2. Paleoecologically-Significant, Descriptive Definitions For Overall Amounts of Bioturbate Textures.

BIOLOGIC DISTURBANCE	DEFINITION
Unworked	descriptive term refers to sediments devoid of biologically-derived textures; these sediments show preservation of physically-emplaced textures and structures
Worked	descriptive term refers to biologically-mediated, previously undisturbed sediments; as such, these sediments show local contrasts between biologically-mediated and physically-emplaced or diagenetic textures; definition implies preservation of original biologically-emplaced textures; single-event exploitations
Reworked	descriptive term refers to biologically-modified, previously bioturbated sediments; textural relationships lack evidence of original biologically-derived textures; multiple-event exploitations

confusion arising from such inconsistent usage of this term, we suggest restricting "bioturbation" to a verb, in reference to generic descriptions of biogenic sediment-mixing processes.

Bioturbate Textures

Bioturbate texture has been defined previously as "gross texture imparted to sediments by extensive bioturbation; typically consists of dense, contorted or interpenetrating burrows or other traces, few of which are distinct morphologically" (Frey, 1973; Frey and Pemberton, 1985). Such textures were described originally as *fossitexture* in the German literature by Richter (1952). This definition of *fossitextura* referred to mottled structures and gross textures that resulted from bioturbation. Similarly, the term *fossitextura deformativa* referred to rocks that showed such mottled structures (Schafer, 1956; Hantzschel and Frey, 1978). Additionally, the early German literature referred to burrow textures as Wühlgefüge (Hantzschel and Frey, 1978).

An understanding of the fundamental definition of "bioturbate texture" is vital to erecting a classification scheme for biologcally-produced sedimentologic relationships on the basis of physical parameters of local heterogeneities in burrowed substrates. This is relevant in the sedimentologic definition of the term "texture," which described mutual relations among carbonate constituents such as bioclasts, peloids, micrite, etc. (Dunham, 1962; Bates and Jackson, 1980). Biogenic alterations of depositional textural relationships between constituent particles included modifications to overall arrangements and productions of burrow fabrics, which defined local heterogeneities. Thus genetically-significant definitions for biogenic textures are proposed (Table 2). These biogenically-modified textures have been described as gross relationships among substrate constituents that resulted from spatial arrangements of burrow fabrics; these consist of local heterogeneities defined by grain-size contrasts and alignments between fills and host substrates, and homogeneous affinities between such aspects. The term "burrow fabrics" refers to a generic descriptor for local biologically-produced heterogeneities that formed genetically-linked, distinct and indistinct structural aspects of bioturbate textures. By definition, burrow fabrics constituted the "building-blocks" of bioturbate textures, and refer inherently to the relative grain size-dimensions and orientations of allochems that comprised local heterogeneities. This contrasts significantly to the widely-accepted definition for its synonym "ichnofabrics."

Ichnofabrics

Ichnofabrics have been defined as "all aspects of the texture and internal structure of a sediment that result from bioturbation and bioerosion at all scales" (Ekdale and Bromley, 1983). Since Bates and Jackson (1980) demarcated "fabrics" on the basis of orientations of sedimentary particles, it is necessary to refer to local, biogenically-produced structures composed of re-oriented, or otherwise heterogeneously redistributed particles as "burrow fabrics" (synonym ichnofabrics). Therefore, "ichnofabrics" as defined by Ekdale and Bromley (1983), and Droser and Bottjer (1986) represents a sedimentological misuse of the word stem "fabrics." Alternatively, Frey and Pemberton's (1990, 1991) reference to "bioturbate textures" as overall relationships among biologically-mediated substrates, is consistent with historical perspectives, and sedimentological and biological connotations.

Furthermore, the term 'ichnofabrics" has been used incorrectly as a "catch-all" expression for generic descriptions of inherent sedimentologic and taphonomic characteristics of bioturbate textures. For example, previous descriptions of ichnofabrics included aspects such as "taphonomic-sediment associations" (Goldring *et al.*, 1991), and "degree of bioturbation, trace fossil preservation, and sediment texture" (Bockelie, 1991). These characterizations omitted important genetic parameters of bioturbate textures including the tenet that such modified arrangements represented truly integrated physiogenic, biogenic and diagenetic entities. Thus, a holistic approach to definition and classification is necessary.

PREVIOUS CLASSIFICATION SCHEMES

Establishing a genetic classification scheme for indiscrete bioturbate textures represents a compelling problem in ichnology. This paper suggests that attributes which render a scheme effective in terms of genetic value and usefulness, include classification on the basis of biological criteria, simplicity and descriptive characteristics, where these attributes provide for practical applications, and yield sufficiently sophisticated data that facilitates an understanding of biotic processes. Classification schemes that show such attributes are consistent philosophically with Seilacher's (1967 b) hypothesis. Previous classifications provided data limited in usefulness and practicality for deriving easily, genetic interpretations of textural origins (Richter, 1952; Schäfer, 1956; Droser and Bottjer, 1986; Bockelie, 1991; Taylor and Goldring, 1993; Miller and Smail, 1997).

Genetically-based, philosophical underpinnings of the Seilacher's (1964, 1967 a, b, 1978) approach to understanding bioturbate textural origins is not shared by many contemporary workers. Differences of opinions on genetic classification schemes have hampered in part, development of consensus among ichnologists and sedimentologists. In spite of divergent viewpoints, or perhaps because of them, many discussions between like-minded trace fossil workers have lead recently to collaborative efforts, which produced a substantial body of ichnological literature. These works proposed a wide range of classification schemes, focused primarily on categorizations of the total amounts of bioturbate textures, including indiscrete fabrics (Richter, 1952; Schäfer, 1956; Droser and Bottjer, 1986; Bockelie, 1991; Taylor and Goldring, 1993; Miller and Smail, 1997). However, this approach is not new (Richter, 1952; Schäfer,1956; Reineck, 1963). Early works on quantitative estimates of bioturbate textures have not been widely adopted, partly because these have shown limited usefulness, except as a basic descriptor. But, these limitations have not deterred some ichnologic workers from proposing a number of schemes with fundamentally similar features. Although semi-quantitative estimations represent the most popular approach to classification, the wide spectrum of schemes proposed included those that showed levels of sophistication from simple and purely descriptive systemizations, to semi-quantitive categories, and complex mathematical and computer-generated models.

Simple, Descriptive Approaches

Simple, descriptive approaches to classifications of bioturbate textures encompassed applications of a wide range of generic terms, including those that were informally-defined (i.e. Young *et al.*, 1983), and terminologies which lacked definitions. In these approaches, most terms utilized for descriptions of bioturbate textures lacked numerical indices and percent categories. Selected examples of purely descriptive terminologies and phrases include "trace fossils rare, trace fossils common" (Rhoads, 1975), "absent, sparse, uncommon, common, abundant" (MacEachern and Pemberton, 1992; Pemberton *et al.*, 1992b), "nil, rare, moderate, common, abundant" (Keswani and Pemberton, 1993), "partially-bioturbated, thoroughly-bioturbated" (Orr, 1994), and "none" to "heavy" degrees of bioturbation (McLellan and Hutcheon, 1995). These descriptions of the total amounts of bioturbate textures, commonly included denotations of numerical indices for respective estimates of disturbed substrates.

Albeit, some classification schemes employed combinations of both descriptive terminologies, and defined limits for the specific amounts of bioturbate textures recorded. These represent schemes considered transitional between purely descriptive approaches, and the semi-quantitative classifications. Selected examples of such schemes include Young *et al.* (1983) and Mountain *et al.* (1994). Young *et al.*'s (1983) scheme proposed the following descriptive classes and designated volumetric limits: "moderate (30-60% bioturbation)," "strong (60-90% bioturbation)," "very strong (90-99% bioturbation)" and "completely bioturbated (100% bioturbation)." Similarly, Mountain's *et al.* (1994) classification provided a modified version of Droser and Bottjer's (1986) semi-quantitative scheme, which included descriptive classes such as "no bioturbation", "slight bioturbation," "moderate bioturbation," "heavily bioturbated," and "homogeneous," that correlated to respective amounts of bioturbate textures, defined by ichnofabric indices. Since these approaches are purely descriptive and devoid of biological connotations, characterizations of bioturbate textures accordingly provide data limited in usefulness for genetic interpretations.

Semi-Quantitive Approaches

Semi-quantitative approaches to classifications refer to the concept of utilizing numerical indices to denote volumetric estimates of biologically-mediated substrates. Recently, many semi-quantitative classification schemes with minor differences between each have been proposed. These schemes are essentially comparable to those proposed earlier (Richter, 1952; Schäfer, 1956; Reineck, 1963). The most popular semi-quantitative scheme erected six classes of ichnofabric indices (Droser and Bottjer, 1986). Recently, this concept has come in vogue, and its applications in sedimentologic and paleoecologic studies have produced a substantial body of literature. Notwithstanding the sizable volume of publications, these semi-quantitative schemes have been advocated mainly by a handful of proponents. Although we are encouraged by the attention focused on the problem of classifying indiscrete bioturbate textures, the bandwagon-effect indicated by the avalanche of recent publications on the ichnofabric concept has resulted unfortunately in escalating some long-standing controversies regarding its significance. Furthermore, concentration of attention on ichnofabric studies has resulted in oversights of the paramount aspects of the ichnologic record: discrete trace fossils, and ichnofacies relationships.

In slightly more than a decade, several semi-quantitative classification schemes for bioturbate textures were proposed independently. Droser and Bottjer (1986) represents the earliest of these recently-proposed schemes, followed by Bockelie (1991), the works of a prominent group of British trace fossil researchers (Pollard *et al.*, 1993; Taylor and Goldring, 1993; Goldring and Pollard, 1993; Goldring, 1995), and Miller and Smail, (1997). Among this assortment of semi-quantitative classification schemes, Droser and Bottjer's (1986) work has received predominant attention.

The foundation of Droser and Bottjer's (1986) semi-quantitative scheme is the concept of ichnofabric indices which designated volumetric grades from classes ii 1 to ii 6 to represent amounts of biologically-disturbed sedimentary fabrics. These categories for ichnofabric indices correlated to the following visually-estimated percentages of disturbed sedimentary fabrics in measured 35 cm by 50 cm vertical cross-sectional areas: 0%, 1-10%, 10-40%, 40-60%, 60-99%, 100%, respectively (Droser and Bottjer,1986). These ichnofabric indices have been applied extensively in ichnological, sedimentological and paleoecological studies (Bottjer, 1987; Droser and Bottjer, 1987; 1988 a, b; 1989 a, b; 1990; 1993; Droser, 1991; Bottjer and Droser, 1991, 1992, 1994; Bottjer *et al.*, 1988, 1995; Crimes and Droser, 1992; Droser, 1995; Droser *et al.*, 1996). Notwithstanding, that these studies represent a substantial body of ichnologic works, we remain apprehensive about genetic applications of the ichnofabric concept.

A similar semi-quantitative classification scheme established five categories for total amounts of bioturbate textures (Bockelie, 1991). This scheme is based on quantifications of the degrees to which sedimentary fabrics have been biologically-mediated (Bockelie, 1991). But, in this scheme, ichnofabric indices were designated in reversed order, where grades 1 and 5 represented the highest and lowest quantities of bioturbate textures, respectively. Coincidentally, these reversed-order grades correlated to Droser and Bottjer's (1986) range of ichnofabrics from completely homogenized substrates (ii 6) to absence of biologically-mediated fabrics (ii 1).

Prominent British workers proposed a more elaborate semi-quantitative classification which consisted of a bifold scheme. This approach established six classes of bioturbation indices (B.I.) 1 to 6, for total amounts of bioturbate textures, and construction of ichnofabric constituent diagrams (Pollard *et al.*,1993; Taylor and Goldring, 1993; Goldring and Pollard, 1993; Goldring, 1995). These diagrams depicted several ichnological parameters including ichnotaxa, burrow diversity and density, and order of ichnofossil emplacements (Pollard *et al.*,1993; Taylor and Goldring,1993; Goldring and Pollard, 1993; Goldring,1995). Proponents of this scheme suggested that such detailed characterizations of bioturbate textures represented an improved method of documenting complexly tiered trace fossils and indiscrete biogenic fabrics. However, consideration of practical applications of this scheme in logging hundreds or thousands of meters of subsurface drill cores has evoked apprehensions regarding its usefulness as an effective ichnological tool.

Mathematical Approaches and Computer-Generated Models

Constructions of mathematical and computer-generated models represent more complex approaches to characterizations of biological mixing processes and developments of bioturbate textures. Several paradigms have been proposed for distinguishing these processes and textures, in both modern and ancient substrates. In studies of modern benthic marine environments, the central themes of proposed mathematical models have been focused mainly on biological mixing rates, depths of bioturbation and transport scales in sediment re-distribution patterns, and on aspects of chemical mass exchanges (Berger and Heath, 1968; Guinasso and Schink, 1975; Aller 1980, 1982b, 1984, 1994; Matisoff, 1982; Boudreau, 1986 a, b, 1997; Boudreau and Imboden, 1987; McCave, 1987; Wheatcroft and Frey, 1990; Cutler, 1993; Wheatcroft *et al.*,1990, 1994). Ekdale *et al.*, (1984) summarized concepts and approaches utilized in early theoretical and empirical studies, where bioturbation has been modelled mathematically. These earlier works included Glass (1969), Nozaki *et al.* (1977), Peng *et al.* (1977, 1979), Berger and Johnson (1978), Williams *et al.* (1978), and Ekdale *et al.* (1984a, b).

Alternatively, in studies of ancient substrates, statistical methods and computer-based image analysis techniques have been applied for delineations of spatial patterns, and apparent relationships between trace fossils in complexly tiered bioturbate textures (Seilacher, 1986; Bromley, 1990, 1996; Ranger and Pemberton, 1991; Magwood and Ekdale, 1994). Since many of these techniques are relatively new, corroborative evidence is required to evaluate their effectiveness in providing data useful for deciphering paleobiologically-, and paleoecologically-significant trends.

LIMITATIONS OF PREVIOUS CLASSIFICATIONS

The preceding discussion highlighted two main schools of thought which pervade modern ichnology: ichnofacies and ichnofabric concepts. This paper affirms the endorsement of Seilacher's (1964, 1967 a, b, 1978) hypothesis: the characteristics of bioturbational products represent fossilized remains of behaviours preserved in ancient substrates; and, ichnofacies relationships provide a genetic framework for understanding distribution patterns of trace fossil assemblages, which represented manifestations of ethologic groups and trophic strategies. But, in order for indiscrete bioturbate textures to be deemed consistent philosophically with this genetic model, classifications of these products on the basis of biologically-significant criteria are required; and constructional elements represent integral aspects of holistic conceptual frameworks that coupled both genetic and spatiotemporal relationships. Shortfalls in previous schemes have been linked inherently to absence of such criteria, and to omissions of respective dynamic frameworks. The lack of standard terminologies, genetic classification schemes, and a comprehensive conceptual foundation have hampered in part, our understanding of the significance of bioturbate textures, and intrinsic relationships in fabric genesis and diagenesis.

Ichnofacies v.s. Ichnofabrics

The strengths of the ichnofacies concept have not been accepted universally (Byers 1982; Goldring, 1993, 1995). Goldring (1993, 1995) outlined a detailed critique of this concept, and suggested that the recent trend toward replacement of ichnofacies by ichnofabrics in facies interpretations was beneficial. Many of Goldring's (1993, 1995) arguments are superficial, particularly those regarding the benefits of the ichnofabric approach (i.e. Goldring and Pollard, 1993; Taylor and Goldring, 1993; Goldring, 1995), total number of ichnofacies, and designations of these assemblages after particular ichnotaxa such as *Cruziana*, even where these trace fossils are absent (i.e. Goldring, 1995). Goldring's (1995, p. 159) criticisms have missed entirely, the crux of the ichnofacies concept. The significance of this concept lies not in its labels, nor its numbers, but rather in the diversity patterns of ichnofossil assemblages, and behavioural manifestations associated with sedimentological parameters. Goldring (1993, 1995) has disregarded the notion that the ichnofacies concept provided a vehicle for understanding the significance of ichnofossils and recurrent assemblages in terms of biotic processes, which modified textural relationships in substrates deposited under particular sedimentary regimes.

Furthermore, Goldring's (1995, p. 159) concerns regarding total numbers of ichnofacies, and the limits of resolution of these are unwarranted. Since standard ichnofacies have remained relatively unchanged in more than two decades, this likely represents an endorsement of Seilacher's (1964, 1967 a, b, 1978) model. A testament to the significance of the ichnofacies framework is the number of summaries presented in comprehensive reviews on ichnology (Ekdale *et al.*,1984; Frey and Pemberton,1984, 1985; Bromley,1990, 1996; Pemberton *et al.*, 1992).

Nevertheless, Byers' (1982) raised a point of contention on the essence of ichnofossil assemblages: the ichnofacies concept has relegated the distributions of organisms and relevant biological processes to the status of mere functional entities, which were significant secondarily to physical factors. Contrarily, the conceptual framework erected by the ichnofacies concept is inclusive and accommodated integration of principal biological and sedimentological parameters. Although we endorse the premise that morphologies and distributions of trace fossils are related intrinsically to biological parameters, it is argued that the ichnofacies concept represents truly an integrated approach to modelling of dynamic paleoenvironments. And, given the biological limitations of ichnology outlined in Ekdale *et al.* (1984a), Bromley (1990, 1996), and Pemberton *et al.* (1992a), the ichnofacies approach and the philosophically-compatible classification scheme proposed herein, are nonetheless sound frameworks for understanding *in-situ* biotic processes, and texture genesis, respectively.

It has been suggested that the recent trend toward replacement of the ichnofacies concept by ichnofabrics represented advancements in trace fossil research (Goldring, 1993; 1995). This paper contends otherwise. The liberation of ichnofossils from an ichnofacies framework represents a non-behavioural approach to the study of biogenic structures, and disregards the notion of fully integrated fabrics, where origins considered implicitly the influence of biological, sedimentological and geochemical regimes. On the contrary, applications of ichnofabric data sets in paleoenvironmental reconstructions and paleoecological studies represent a non-genetic approach. If trace fossils were divorced from genetic underpinnings, how might we evaluate the significance of biotic processes and recurrence of ichnofossil assemblages, in relation to sedimentological and geochemical parameters?

Applications of Ichnofabrics in Sedimentology

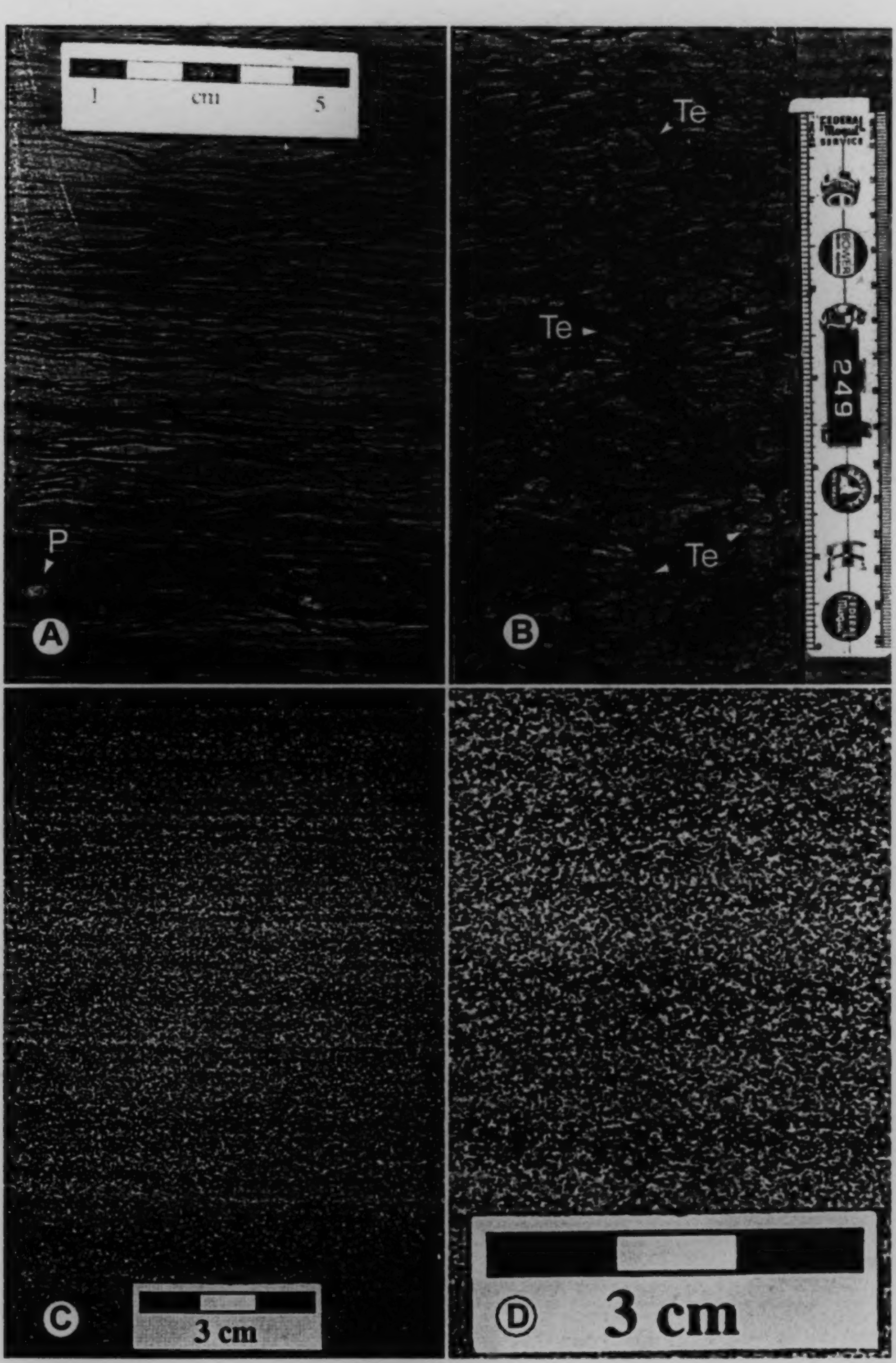
Problems arise from genetic applications of non-genetic classification schemes such as semi-quantitative ichnofabrics in sedimentological studies. The limitations of the ichnofabric concept are linked inherently to the use of total amounts of biogenically-disturbed substrates for interpretations of textural origins. Since bioturbate textures have been classified merely on this basis, and not on criteria indicative of paleobiological processes, we considered applications of ichnofabric data essentially a non-genetic approach that yielded data devoid of usefulness for understanding origins. Goldring and Pollard (1993), Taylor and Goldring (1993) and Goldring (1993, 1995) have overstated many of the so-called advantages of the ichnofabric approach. Droser and Bottjer (1993) suggested consideration of merely discrete trace fossils represented incomplete ichnological and sedimentological data sets. We take exception to this suggestion, in view of the contention that classes for total amounts of bioturbate textures are devoid of genetic significance. Classes of ichnofabrics do not reflect behavioural constraints, nor associated paleoenvironmentally- and paleoecologically-significant gradients. Therefore, we suggest studies which utilized ichnofabrics for genetic interpretations warrant reassessment.

Inherent problems related to utilizations of the ichnofabric concept in sedimentology and stratigraphy are illustrated by providing examples. These problems are related mostly to modes of texture genesis (Wheatcroft and Frey, 1990). Equivalent ichnofabrics may have fundamentally distinct origins and visual appearances (Wheatcroft and Frey, 1990). Comparable amounts of bioturbate textures are produced by distinct biotic processes and paleocommunities, in response to particular sedimentary regimes and paleoecological conditions (Ekdale *et al.*, 1984a; Bromley, 1990, 1996; Pemberton *et al.*, 1992a,b; Keswani and Pemberton, 1993). Yet, in terms of ichnofabrics, these textures are characterized by similar indices (Figures 1,2). Therefore, interpretions based solely on ichnofabric data likely result in inaccurate sedimentological reconstructions.

Sedimentological studies that utilized ichnofabrics are rife with problems. These inconsistencies have been illustrated by comparisons of bioturbate textures developed in substrates deposited in four distinct paleoenvironments. Such burrowed substrates included those deposited in oxygen-depleted, salinity-stressed, fully-marine shelfal, and lower shoreface-nearshore paleoenvironments. These substrates have been characterized by comparable levels of ichnofabrics, for approximately equivalent, total amounts of bioturbate textures; yet, these have commonly shown ichnotaxonomically-distinct signatures (Bromley and Ekdale, 1984; Savrda *et al.*, 1984; Ekdale, 1985; Savrda and Bottjer, 1986, 1987, 1989, 1991; Ekdale and Mason, 1988; Vossler and Pemberton (1988, 1989); Föllmi and Grimm, 1990; Wignall, 1991, 1993; MacEachern and Pemberton, 1992; Savrda, 1992, 1993; Keswani and Pemberton, 1993; Droser and Bottjer, 1993, Figure 1A; Savrda and Sageman, 1994; Saunders *et al.*, 1994; Allison *et al.*, 1995, p. 100). These trace fossil assemblages reflected distinct sets of behavioural responses to local paleoecological conditions (Figures 1,2).

Characterizations of low-oxygen substrates in terms of ichnofabric data lacked resolution for detailed paleoenvironmental reconstructions. For example, consider total amounts of bioturbate textures developed in oxygen-depleted substrates. These have been assigned ichnofabric indices ii 4 to ii 6 (Droser and Bottjer, 1993, Figure 1A). But, Robbins (pers. com.) documented substrates nearly barren of benthic organisms in some of these paleoenvironments (Figure 1A). Typically, ichnofossils emplaced in such strata consisted of monospecific and low-diversity assemblages dominated *Chondrites,* and include *Planolites*, *Thalassinoides*, and *Zoophycos*, locally (Bromley and Ekdale, 1984; Savrda and Bottjer, 1986, 1987, 1989; Ekdale and Mason, 1988; Droser and Bottjer, 1993, Figure 1A). However, Wignall (1991) and Allison *et al.* (1995) alluded to limitations of utilizing *Chondrites* as diagnostic indicators of oxygen-depleted substrates.

Figure 1. Textural relationships in selected ancient clastic deposits. (A) Depositional textures preserved in laminae within a muddy siltstone unit from the Triassic Montney Formation, 11-28-62-19W5, depth 6660'. Preservation of original sedimentary structures and textural relationships within these units have been interpreted as reduced-oxygen substrates, where inhospitable conditions precluded colonization (Robbins, pers. com.). Isolated *Planolites* characterize the ichnological attributes of this mostly unworked interval. (B) Worked and reworked bioturbate textures in the Lower Cretaceous Grand Rapids Formation show a *Teichichnus*-dominated ichnofossil assemblage within an interlaminated mudstone and siltstone (Beynon, 1990; Beynon and Pemberton, 1992). These substrates represent deposition in brackish-water paleoenvironments. Comparison of oxygen- and salinity-stressed substrates (A,B) show differences in both the sedimentological and ichnological parameters locally, and in the preservation of textural relationships. (C) Large-scale view of the Cadotte member of the Lower Cretaceous Peace River Formation west-central Alberta shows preservation of laminae in sand deposits, 07-26-68-09W6, depth 1899 m. These sandstones have been interepreted as deposition in high-energy, wave/storm-dominated beach-shoreface paleoenvironments (Saunders *et al.*, 1992) (D) Close-up view of the Cadotte member sands show completely worked substrates, where cryptic bioturbate textures have been defined by mm-scale irregularities in boundary layers that constituted the laminae in 07-26-68-09W6, depth 1898 m. Note the differences in textural parameters and preservational styles of the laminae in stressed (A) and fully-oxygenated marine substrates (D).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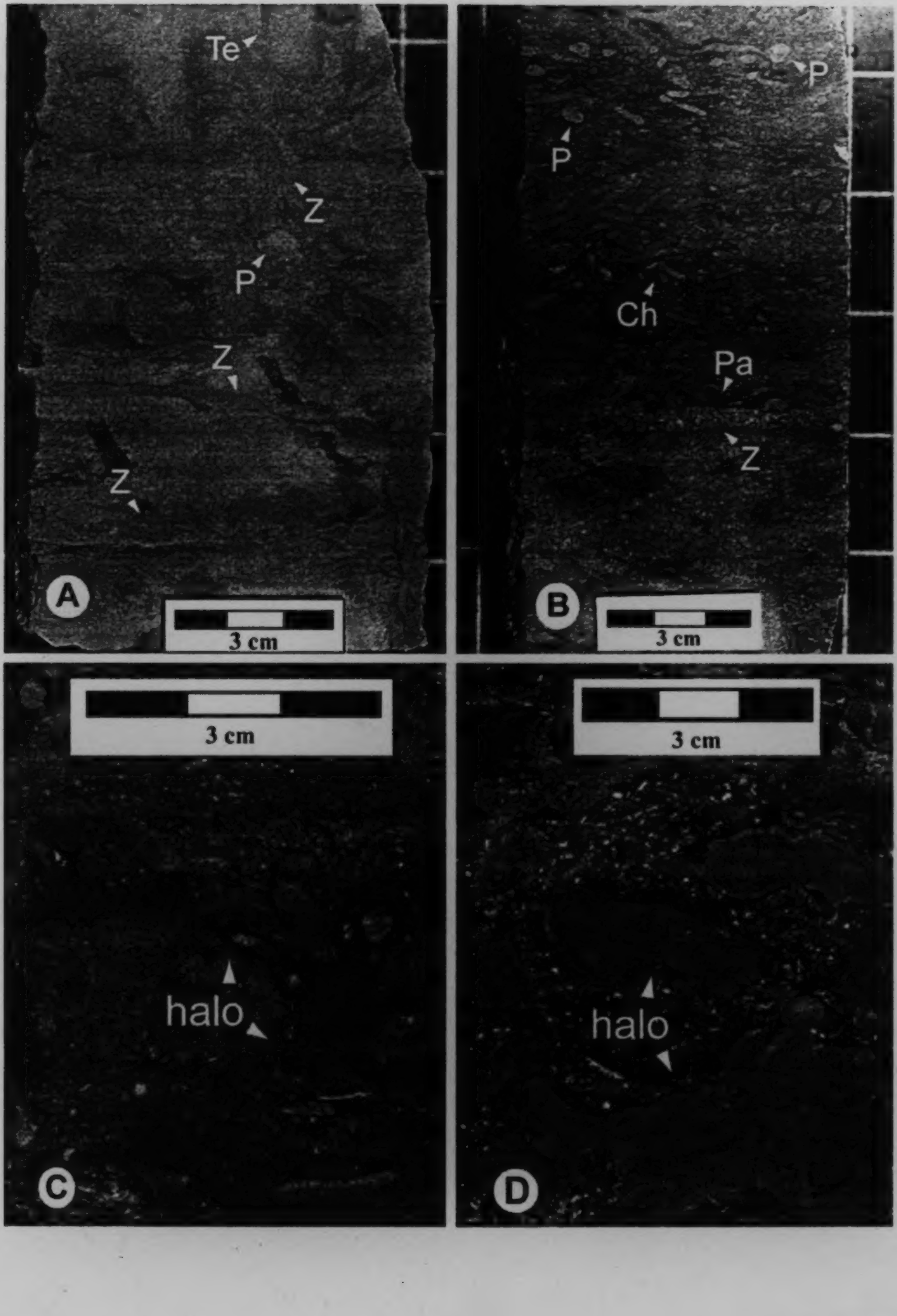
Furthermore, we referred to the works of Vossler and Pemberton (1988, 1989) to highlight that similar amounts of bioturbate textures, characterized by approximately equivalent ichnofabric indices and predominance of *Chondrites,* have been recognized in fully-oxygenated substrates, deposited in storm-influenced, shelfal paleoenvironments.

Alternatively, similar amounts of bioturbate textures have been documented in substrates representative of brackish-water paleoenvironments. Beynon (1991) and Beynon and Pemberton (1992) documented a low-diversity, *Teichichnus*-dominated ichnofossil suite, which included subordinate ichnogenera such as *Planolites*, *Skolithos*, and rare *Asterosoma*, *Chondrites*, *Gyrolithes* and *Rhizocorallum* (Figure 1B). These substrates showed relatively high volumes of bioturbate textures, approximately equivalent to ichnofabric indices that ranged from ii 4 to ii 6, locally. Comparisons of substrates deposited in such salinity stressed conditions, to those that accumulated in fully-marine paleoenvironments have shown that approximately equivalent amounts of bioturbate textures, correlatable to ichnofabric indices ii 4 to ii 6, characterized both strata (Vossler and Pemberton, 1988, 1989; Beynon,1991; Beynon and Pemberton, 1992; Keswani and Pemberton, 1993, Figure 5). But, fully-marine substrates showed a diverse suite of ichnofossils. For example, biogenic structures created in ambient substrates (Figure 2A,B) interpreted as fairweather deposits of the outer shelf included *Thalassinoides*, *Planolites*, *Asterosoma*, *Zoophycos*, *Chondrites*, *Subphyllochorda*, *Palaeophycus*, *Teichichnus*, *Rhizocorallum* and *Helminthopsis* (Keswani and Pemberton, 1993). These examples have demonstrated that approximately equivalent amounts of bioturbate textures and respective ichnofabric indices characterized substrates deposited by unlike sedimentary regimes; but, ichnofossil diversity patterns provided the genetically-significant data useful for interpretations of distinct paleobiological processes in these paleoenvironments.

In addition, applications of the ichnofabric concept in sedimentologic studies of substrates characterized by cryptic bioturbate textures are problematic. These textures described commonly in the literature as "cryptobioturbation," represented biogenically-mediated substrates that showed preservation of sedimentary fabrics (Howard and Frey, 1975; Saunders *et al*., 1994). For example, cryptic bioturbate textures characterized by abundant *Macronichnus* have been developed in sandy upper shoreface-foreshore

Figure 2. A clustered interpenetrating and homogenized bioturbate textures in selected ancient carbonate deposits, Williston Basin, Saskatchewan. (A,B) Reworked dolomudstones and dolowackestones in the Mississippian Midale carbonates, well 7-1-5-19W2. These deposits comprise parts of the muddy facies association. (A) Muddy deposits at depth 1714.17 m characterized by a diverse ichnofossil suite, including *Zoophycos* (Z), *Planolites* (P), and *Teichichnus* (Te). (B) The muddy facies at depth 1708.40 m shows the ichnofossils *Planolites* (P), *Chondrites* (Ch), *Zoophycos* (Z), and *Palaeophycus* (Pa). (C,D) Reworked dolomudstones and dolowackestones in the Ordovician Yeoman Formation, at the Imperial Hummingbird well 6-13-02-19W2. The homogenized bioturbate textures are characterized by an abundance of indistinguishable reworked fabrics, and by vestiges of structures locally. (C) Textural heterogeneities defined by reworked fabrics, including preservation of organic linings and diagenetic halos around some unidentifiable structures at depth 9924 ft. (D) Heterogeneous textures defined by vestiges of unidentifiable burrow fabrics and surrounding diagenetic halos developed at depth 9892 ft. Such textural heterogeneities clearly show the profound impact of bioturbation on diagenesis. Note the volumes of sediments that comprise diagenetic halos around some burrow fabrics exceed the amounts of the fills within those structures.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substrates that showed preservation of laminae (Saunders *et al.*, 1994). Since ichnofabric indices have been defined on the basis of total amounts of biologically-disturbed physical structures, these thoroughly burrowed, sandy substrates are characterized aptly by an ichnofabric index ii 1, rather than an ii 6 (Figure 1C,D). Thus, classifications of cryptic bioturbate textures on the basis of ichnofabrics, result in inaccurate descriptions of the levels of biological mediation. Such inaccuracies are linked inherently to utilizations of non-genetic criteria for erections of semi-quantitative classification schemes. These examples have demonstrated that totalities of bioturbate textures have diverse sedimentological, paleobiological and paleoecological values, which limited severely, usefulness for interpretations of textural origins. Therefore, ichnologists and sedimentologists must rely on recognition of discrete biogenic structures, and ichnofacies relationships for such genetic interpretations.

Applications of Ichnofabrics in Stratigraphy and Basin Analysis

The ichnofabric concept has been applied in stratigraphic correlation and basin analysis (Bockelie, 1991; Bottjer and Droser, 1991). These studies required interpretations of genetically-linked strata in basin fills, and delinations of spatial relationships in facies distributions. Since ichnofabrics have been utilized to decipher many of these genetic relationships, the sedimentologic limitations of this concept are relevant. In particular, limitations are pertinent in use of ichnograms, the normalized ichnofabric data that have been utilized for characterizations of distribution patterns of the total amounts of bioturbate textures in sedimentary facies (Bottjer and Droser, 1991). The proponents of this concept claimed these characterizations of facies showed the range of ichnofabric indices, which contributed toward a "more complete summary of biogenic structures" (Bottjer and Droser,1991, p. 201). Bottjer and Droser (1991) took applications of ichnofabrics one step further and suggested calculations of average ichnofabric indices for characterizations of specific facies. Due to the non-genetic base of ichnofabric indices, and their somewhat subjective applications in sedimentological and ichnological studies, these mathematical manipulations produce data sets that represent abstract paleoecological concepts, where claims of usefulness have been exaggerated. Therefore, we caution against the use of ichnograms and mean ichnofabric indices, since these represent rather redundant calculations on numerical data devoid of biologic significance.

Careful consideration of the concept of mathematical computations on ichnofabric data sets shows flaws apparent in this approach to the characterization and interpretation of indiscrete bioturbational products. The following problems arise from manipulations of data on indices that designated relative amounts bioturbate textures: (1) the resultant ichnofabric values represent an abstract concept with no real bearing on relationships between the character of bioturbate textures and biotic processes, and (2) the genetic limitations of ichnofabrics are "carried forward" in calculations and rendered the results similarly restricted. Consequently, stratigraphic correlations on the basis of similar ichnofabrics (i.e. Bockelie, 1991), and mapping sedimentary facies distributions for understanding basin fills and evolution (i.e. Bottjer and Droser, 1991), represent mostly non-genetic spatial relationships. Thus, many inferences derived on textural origins in these studies are likely untenable. Furthermore, confusion may arise in stratigraphic correlations, where comparisons between bioturbate textures classified differently have been considered.

To avoid shortcomings in applying the ichnofabric concept in stratigraphical and paleoenvironmental studies, ichnofabric workers have modified this approach and ascribed textures to specific ichnogenera, particularly after dominant trace fossils and assemblages that produced individual fabrics (Bockelie, 1991). Examples of such ichnofabrics included those named after *Skolithos*, *Ophiomorpha*, *Anconichnus*, *Helminthoida*, *Palaeophycus*, and *Diplocraterion*, and *Rosselia* (Droser and Bottjer, 1987, 1988, 1993; Bockelie, 1991; Droser 1991; Goldring *et al.*, 1991; Pollard *et al.*, 1993; Taylor and Goldring, 1993 Bottjer and Droser, 1994). However, this solution to problems associated with interpretations of textural origins on the basis of ichnofabric data has two major flaws: (1) the ichnofacies concept hitherto provided a genetic framework for inferences of the significance of discrete trace fossils and recurrent suites; and (2) since ichnofabrics referred to all aspects of textures, including totalities of discrete biogenic structures and indiscrete fabrics, it remained unclear whether the indistinct bioturbational products were attributable directly to specific biotic processes that created ichnogenera in associated substrates. Since individual ichnofabrics have been named merely after dominant ichnogenera, this characterization is flawed because the roles of biotic processes in generating earlier fabrics and respective taphonomic signatures have been disregarded. The lack of genetic relationships between incremental classes of bioturbate textures in semi-quantitative schemes has resulted in omissions of the concept of intrinsic biological influences on taphonomic characteristics. This contributed in part, to the incompatibility of genetic applications of ichnofabric data, and combinations of such with genetically-significant ichnogenera for interpretations of textural origins, particularly in thoroughly burrowed substrates.

Applications of Ichnofabrics in Paleoecology

The ichnofabric concept has been utilized in many paleoecological investigations. Most studies have focused on estimations of the amounts of bioturbate textures recorded in disparate Phanerozoic strata, and interpretations of the significance of differences, in extents to which substrates were burrowed (Droser and Bottjer, 1988 a, b, 1989 a, 1990, 1993; Crimes and Droser, 1992; Bottjer and Droser, 1994; Droser 1995; Droser *et al.*, 1996). These studies suggested increased amounts of bioturbate textures in younger Paleozoic strata indicated expansions in ecospace utilization, and radiations of metazoans into deeper endobenthic habitats during the early Paleozoic, and increased depths of substrate occupation shifted coevally from onshore to offshore paleoenvironments (Droser and Bottjer, 1988 a, b, 1989 a, 1990, 1993; Crimes and Droser, 1992; Bottjer and Droser, 1994; Droser 1995; Droser *et al.*, 1996). However, Pickerill (1992) disputed these interpretations, and suggested deep burrowers occupied substrates during periods as early as the Cambrian. This data refutes, or at least introduces uncertainty to the suggestion based on ichnofabrics, that benthic organisms evoloved differentially in terms of utilizations of substrates deposited in shallow- and in deep-water environments.

The significance of the ichnofabric concept in applications to paleoecological studies regarding habitat use has been largely exaggerated. Since ichnofabrics represent a non-genetic approach to understanding origins, these semi-quantitative classification schemes cannot be applied in paleoecological studies for understanding biotic processes, and intimate relationships between ancient organisms and paleoenvironments. The following question is posed on the nature of increased ichnofabrics developed in later Paleozoic strata: what is the genetic basis for hypothesizing greater amounts of bioturbate textures reflected intrinsically paleobiological escalations, and paleoecologically-significant colonizations of more suitable, deeper endobenthic habitats, and for behavioural evolution? This question has drawn attention to the unsubstantiated viewpoint that greater habitat use has been attributed directly to increased amounts of bioturbate textures, but without genetic linkages to specific biotic processes and paleoenvironmental changes. Therefore, interpretations based soley on ichnofabric data lacked tenable genetic foundations for affirmations of relationships between substrate characteristics and specific biotic processes. This approach contrasts significantly with studies on depths of bioturbation, which suggested progressions of paleobiological sediment-mixing processes into deeper levels, evolved coevally with emergence of land plants (Seilacher, 1978b; Larson and Rhoads, 1983; Jumars *et al.*, 1990, p. 94).

Applications of Ichnofabrics in Carbonate Diagenesis

Estimations of ichnofabric indices in many bioturbated and diagenetically-altered detrital carbonate deposits are problematic. Keswani and Pemberton (1997, 1998, in press) coined the term "paleobiologically-influenced" for biogenically-produced heterogeneous textures and associated variations in diagenetic fabrics. These diagenetic alterations include fabric-selective dolomites, which formed in part, significant aspects of textural relationships, locally (Beales, 1953; Murray and Lucia, 1967; Buchbinder and Friedman, 1970; Bathurst, 1975; Kendall, 1977; Morrow, 1978; Jones *et. al.*, 1979; Choquette and Steinen, 1980; Narbonne, 1984; Pickerill *et. al.*, 1984; Bathurst and Land, 1986; Theriault and Hutcheon, 1987; Banner *et. al.*, 1988; Cander *et. al.*, 1988; Chow, 1991; Keswani and Pemberton, 1993, 1997, 1998; Chow and Longstaffe, 1995).

However, the usefulness of the ichnofabric concept for estimations of total quanitities of paleobiologically-influenced textures is somewhat limited, and stems mostly from the effects of both mechanical and chemical diagenesis. For example, compactional processes in mechanical diagenesis play important roles in determining the taphonomic integrity and the physical characteristics of many bioturbate textures (Shinn and Robinn, 1983; Archer, 1984; Clari and Martire, 1996). Furthermore, nonmimetic dolomitization (Bullen and Sibley, 1984; Sibley, 1991) and a variety of alternate fabric-destructive recrystallization processes associated inherently with bioturbate textures, either occlude or enhance local developments of paleobiologically-influenced diagenetic fabrics (Keswani and Pemberton, 1993). Consider bioturbate textures that showed developments of significant amounts of diagenetic "halos" on the margins of discrete biogenic structures, and in zones of indiscrete fabrics (Figure 2C,D). In many of these deposits, total volumes of such paleobiologically-influenced diagenetic textures exceed the amounts of burrowed fabrics. Thus, a question arises on how to use the ichnofabric approach for accurate estimations of the total quantities of paleobiologically-mediated substrates.

CONGRUENCE BETWEEN ICHNOFACIES AND CONCEPTUAL FRAMEWORKS FOR GENETIC-SPATIOTEMPORAL RELATIONSHIPS

Since contemporaneous organism-sediment interactions generated bioturbate textures that consists of both discrete trace fossils and indiscrete fabrics, these inherently represented genetically-congruent products. Seilacher's (1964, 1967) ichnofacies provided a conceptual framework for understanding biotic processes from identifications of discrete trace fossils, and from recognition of sedimentologically-significant distribution patterns in recurrent ichnofossil assemblages. But, most genetic studies of indiscrete bioturbate textural heterogeneities have been plagued by distinctly incongruous philosphical perspectives.

Alternatively, Keswani *et al.*, (1995) proposed an approach to classification, where a genetically-based scheme provides data useful for understanding origins of indiscrete bioturbate textures. This approach in studies of biologically-produced textural heterogeneities rendered our conceptual basis of classification congruent to the analogous ichnofacies framework in a comprehensive genetic model (Seilacher, 1964, 1967, 1978;

Keswani and Pemberton, 1998). Such congruence in conceptual foundations for textural relationships has been illustrated as equivalent genetic entities, positioned on similar hierarchies (Figure 3).

The notion of congruence between the ichnofacies concept and Keswani *et al.*,'s (1995) genetic classification scheme for indiscrete bioturbate textures has significant implications regarding the effects of paleobiological processes in an overall model for textural evolutionary dynamics (i.e. Keswani and Pemberton, 1998). Parallel applications of both the ichnofacies concept and the classification scheme of Keswani *et al.* (1995), and emplacements of these constructional fabrics in the genetic-spatiotemporal frameworks proposed in Keswani and Pemberton's (1998) model renders insignificant, problems related to scales in applications of these conceptual foundations useful for interpretations of textural origins. Furthermore, this congruence in genetic and scale relationships rendered consistent, paleobiological interpretations of both discrete and indiscrete aspects of bioturbate textures at local and regional scales. However, consistency is required in applications of such paleobiological principles for interpretations of processes based on data derived from drill core and outcrop studies. Consequently, interpretations of paleoecological dynamics are based on genetic congruence in origins of morphological, textural and spatial characteristics, and on ichnotaxonomic diversity patterns, which defined the relationships between both ichnofossils, and classes of indiscrete burrow fabrics

The conceptual model proposed for textural evolution integrated genetically, both discrete and indiscrete bioturbational products, where equivalent sedimentological elements defined essentially, physical relationships between Seilacher's (1964, 1967) ichnofacies and congruent genetic classification scheme for bioturbate textures. Equivalent sedimentologic gradients provide the common foundation that couples both the ichnofacies, and genetic-spatiotemporal frameworks. Since geochemical attributes represent an integral part of our conceptual model, the genetic congruence between both these conceptual frameworks established connectedness in distribution patterns of physically- and paleobiologically-derived textures, and diagenetic fabrics associated inherently with such bioturbated substrates at various scales. This standardization of genetically-significant

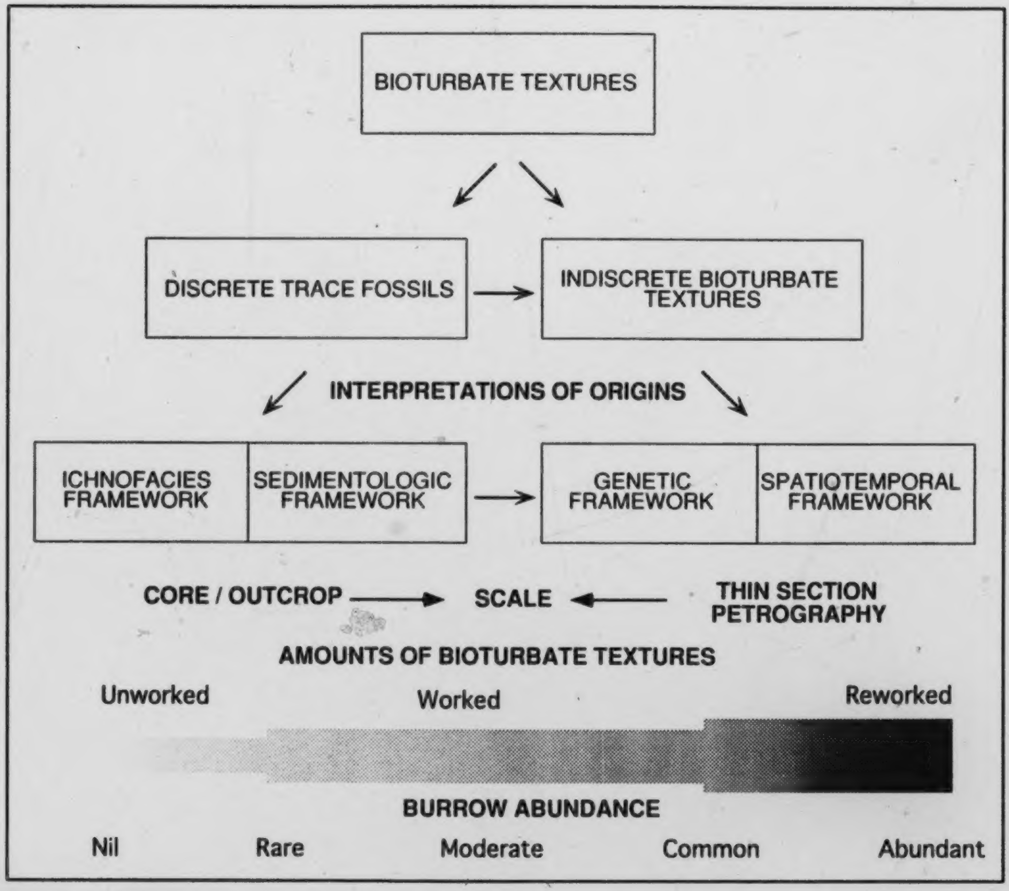


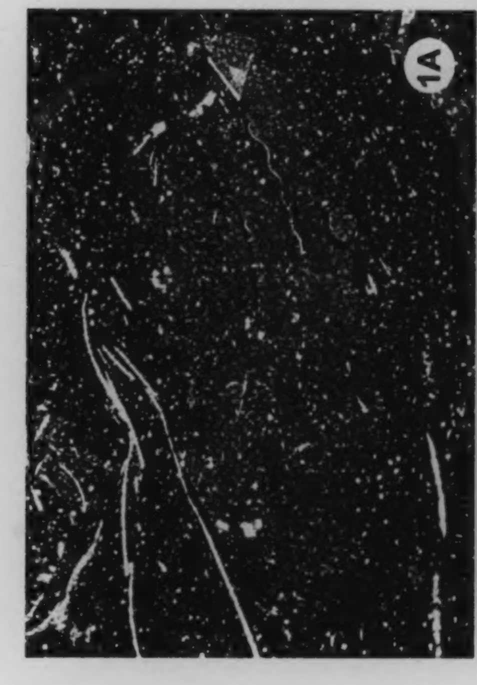
Figure 3. Scales and Genetic Congruence in Applications of Conceptual Frameworks For Discrete Trace Fossils and Indiscrete Bioturbate Textures.

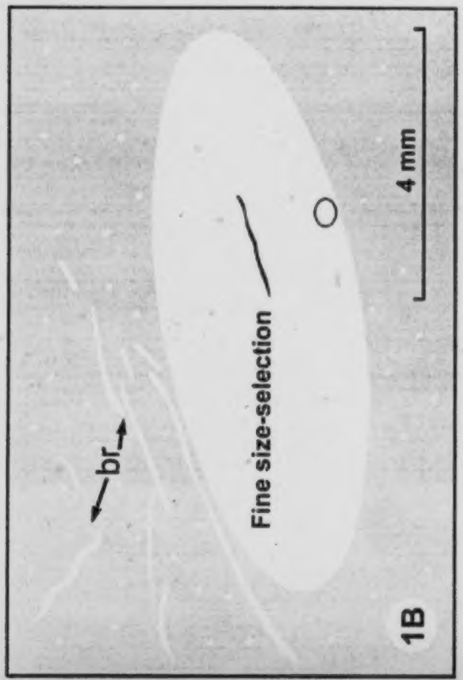
textural linkages in a sedimentological framework facilitated interpretations of intrinsic paleobiological controls on origins of characteristic diagenetic fabrics at various scales. Furthermore, such genetic congruence facilitated integration of data on paleoecological entities derived in studies on drill cores and outcrops, and in thin-section petrography.

The model proposed for textural evolution includes conceptual frameworks for genetic and spatiotemporal elements manifest in both physical and mineralogical characteristics of constructional fabrics. These frameworks have been designed to establish relationships between paleobiological, sedimentological and geochemical processes, and respective spatiotemporal relationships in an integrated model for paleoecological-geochemical dynamics. This genetic approach to conceptual modelling, provides a vehicle for understanding the nature of direct and indirect interplays among processes. Since coupled physical-geochemical parameters of bioturbate textures represent integrated genetic entities, correlation of spatiotemporal scales associated with these inherent relationships facilitate interpretations of evolutionary dynamics. This classification scheme and extension of Seilarcher's (1964, 1967) genetic principles to indiscrete bioturbate textures represented merely an initial step toward an understanding of texture genesis and diagenesis.

To decipher intrinsic controls, particularly the effects of contemporaneously-produced bioturbate textures on developments of late-stage diagenetic fabrics, specific classes of textural heterogeneities (Figures 4,5) required emplacement into our conceptual frameworks. This approach facilitates interpretations of the roles of contemporaneous biotic processes in generating modified textures, which influenced distribution patterns of nucleation sites, crystal growth forms, and spatial relationships in various diagenetic fabrics, such as in selectively dolomitized burrow fills (Keswani and Pemberton, 1997, 1998). Such paleobiologically-influenced diagenetic fabrics are in part, probable indicators of texture-controlled, enhancements of local permeable zones that affected migration pathways of late-dolomitizing fluids (Beales, 1953; Murray and Lucia, 1967; Buchbinder and Friedman, 1970; Bathurst, 1975; Kendall, 1977; Morrow, 1978; Jones *et. al.*, 1979; Choquette and Steinen, 1980; Narbonne, 1984; Pickerill *et. al.*, 1984; Bathurst and Land, 1986; Theriault and Hutcheon, 1987; Banner *et. al.*, 1988; Cander *et. al.*, 1988; Chow, 1991; Tedesco and Wanless, 1991; Keswani and Pemberton, 1993 1997, 1998; Chow and

Figure 4. Thin-section photomicrographs and schematics show bioturbate textural heterogeneities defined by grain-size selection and alignment of allochems. These local heterogeneities comprise burrow fabrics emplaced in the Mississippian Midale carbonates, Williston Basin, Saskatchewan. (1A,B) A distinct burrow fabric emplaced in a bioturbation-derived dolomudstone-dolowackestone at well 7-1-5-19W2, depth 1717.72 m. The sharply-defined wall structure likely resulted from fine grain-size selection of the burrow fills. The oval shape of this structure reflects its partly compressed morphology, which resulted from compaction. Further evidence of such mechanical diagenesis include the fractured and locally-displaced fragments of thin brachiopod (br) shells. (2A,B) A bioturbation-derived skeletal dolowackestone/dolomudstone at well 12-24-3-20W2, depth 6251.13 m shows planar alignment of fecal pellets comprised of micrite. This local heterogeneity is defined by a distinct/indistinct burrow fabric, which represents an ichnotaxonomic equivalent of *Tomoculum*. Both the physical attributes of microfill grain-size, and the morphological characteristics of aligned pellets define the wall structure of this distinct/indistinct burrow fabric. Allochems in these reworked textural relationships include crinoids (cr) and brachiopod (br) skeletons.


1A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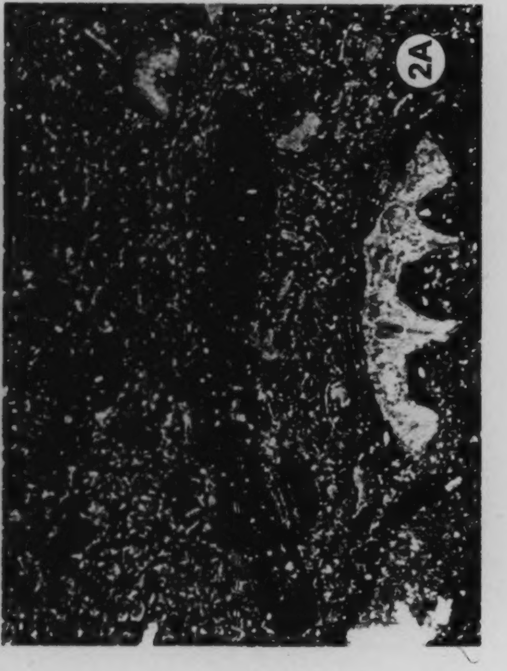
1B


2A

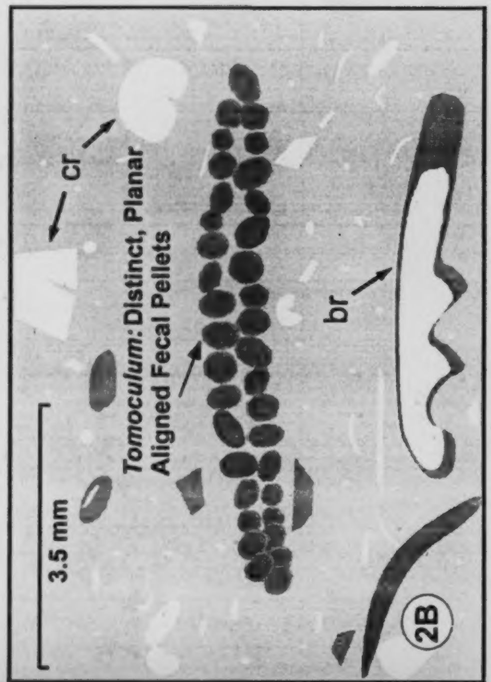
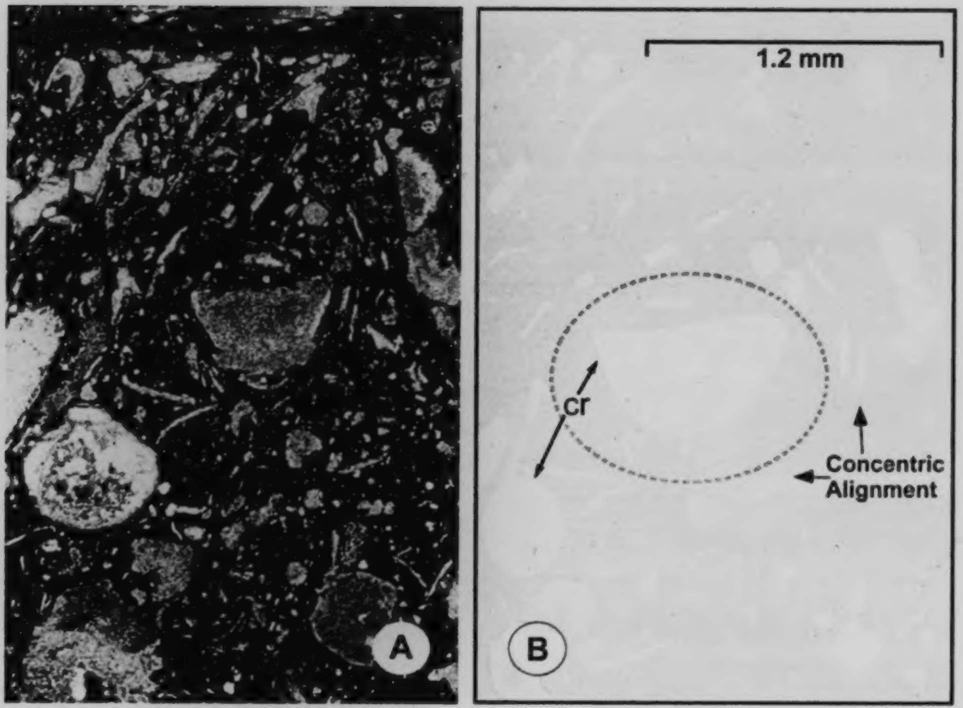

3.5 mm
cr
Tomoculum: Distinct, Planar Aligned Fecal Pellets
br
2B

Figure 5. Thin-section photomicrograph and schematic show a bioturbation-derived wackestone in the Mississippian Midale carbonates at well 12-24-3-20W2, depth 6279.3 ft. This bioturbate texture shows a local heterogeneity comprised of indistinct burrow fabric defined by concentric alignment of elongate skeletal fragments around a crinoid (cr) ossicle. Note the partial alignment of allochems on the margin of the structure. These local variations in textural relationships suggest that the effects of bioturbation extend beyond the boundary of the structure to the host substrates in the immediate vicinity.


1.2 mm
cr
Concentric
Alignment
A
B

Longstaffe, 1995). Furthermore, bioturbate textures likely influenced the rates and extents of many geochemical dynamics (Keswani and Pemberton, 1997, 1998a,b). Thus, classification schemes devoid of genetic significance and congruence to Seilacher's (1964, 1967) ichnofacies framework, lacked the conceptual foundation required for understanding fabric evolution, and linkages between texture genesis and diagenesis.

CONCLUSIONS

The ichnofabric concept has a controversial history. Modelling total amounts of bioturbate textures has been problematic to both ichnologists and sedimentologists. Critical analysis of proposed classification schemes and applications of the ichnofabric concept, showed data sets have limited usefulness in genetic interpretations. These schemes varied from simple descriptive approaches and semiquantitative methods, to mathematical and computer-based models. Data sets derived from applications of these schemes are limited merely to descriptions of bioturbate textures. This genetic limitation is based fundamentally in the absence of a biological foundation for classification schemes. Applications of such non-genetic data sets in both ichnology and sedimentology rendered many inconsistencies in interpretations of textural origins. Alternatively, a genetic approach to understanding the mechanisms of bioturbate texture genesis suggests use of biological criteria for construction of classification schemes, provides a sound foundation for evaluations of paleoecological dynamics.

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CHAPTER 4

CONCEPTUAL MODEL FOR PALEOBIOLOGICALLY-INFLUENCED TEXTURE GENESIS AND DIAGENESIS: GENETIC AND SPATIOTEMPORAL FRAMEWORKS

INTRODUCTION

A process approach to petrographic study of textural relationships in ancient detrital carbonate deposits facilitated the categorization of a complex array of genetic data. These categories included physiogenically-, biogenically-, and diagenetically-derived fabrics and textures. However, conventional petrographic analysis of these deposits focused primarily on the identification of skeletal components, classifications of textural relationships, and on the recognition of distinctive diagenetic fabrics. Traditionally, petrographic studies regarded paleobiological and diagenetic aspects of textural relationships as discrete entities that required independent study. These studies commonly ignored ichnological aspects altogether, or described paleobiologically-influenced fabrics and textural relationships, merely as products of physical and diagenetic processes.

An independent approach to petrographic analysis of ancient detrital carbonate deposits has produced somewhat fragmentary data sets. Previous models constructed for understanding the mechanisms of texture genesis and diagenesis are based essentially on these incomplete data sets. Consequently, many genetic interpretations show disconnections between the mechanisms that influenced origins of fabrics and textures.

Absence of a holistically-based, conceptual model contributed significantly to the restricted focus of previous studies, and to the disassociation between mechanisms in texture genesis and diagenesis. The lack of such a conceptual model resulted in somewhat incomplete interpretations of the genetic relationships in textural evolution. For example, some diagenetic studies have completely disregarded the effects of paleobiological processes on textural developments that influenced diagenetic mechanisms. Hence, a conceptual model that integrates fully, genetic relationships including effects of direct interplays and indirect feedback interactions is required for physical, paleobiological and geochemical processes, and respective spatiotemporal dynamics. Such an integrated model provides a foundation for genetic interpretations, based on the concept of interdependence between processes and fabrics, and their controls on subsequent textural changes.

This paper proposes a conceptual model for textural relationships. Our model proposed these relationships developed through fabric evolution, and physical and mineralogical characteristics manifest cumulative effects of physical, paleobiological and geochemical processes. The fundamental base of the proposed model is the concept of intrinsic linkages in texture genesis and diagenesis. This concept implies that constituent fabrics in local heterogeneities represent inseparable genetic and spatiotemporal entities, and both the physical and mineralogical characteristics reflect the dynamic relationships between processes that influenced textural changes. Accordingly, the proposed model for textural evolution represented constructional fabrics as fully integrated entities, and erected conceptual frameworks for both genetic elements, and respective unique and overlapped spatiotemporal relationships. Thus, analysis of genetically-significant characteristics reflect integral aspects of processes, and respective spatiotemporal elements associated with textural evolution.

LIMITATIONS OF PREVIOUS TEXTURAL CLASSIFICATIONS

Genetic inconsistencies are present in previous models of textural origins for ancient detrital carbonate deposits. These inconsistencies pertain mainly to terminologies, and sedimentological applications of data on bioturbate textural relationships. Although such textural relationships represent common features of most deposits, conventional petrographic analyses have disregarded completely ichnologic aspects, or described such relationships in non-genetic terms as "burrowed," "bioturbated," "nodular" and "burrow-mottled." Furthermore, these studies classified erroneously, biogenically-produced textures in terms of depositional sedimentary relationships according to Dunham's (1962), or alternate schemes. This approach to classification represents an inconsistent application of schemes designed for physiogenically-derived textural relationships.

Applications of a biostratinomic conceptual framework for understanding textural origins, and in sedimentological reconstructions represent a significant advancement toward synthesis of genetic elements manifest in taphonomic signatures (Kidwell *et al.*, 1986). This framework integrated aspects of complex textural developments, including paleobiological parameters, into a preservational model for skeletal deposits (Kidwell *et al.*, 1986). However, this scheme and alternate approaches to classification are limited in usefulness for genetic interpretations of bioturbate textures, and evolutionary dynamics manifested in associative physical-mineralogical characteristics of fabric developments. For example, the biostratinomic scheme classified collectively, the roles of biotic processes, in non-paleoecological categories (Kidwell *et al.*, 1986). Therefore, effects of specific biotic processes on diagenesis cannot be linked genetically, on the basis of physical and mineralogical characteristics of textural relationships derived from paleoecological-geochemical dynamics. Although the conceptual framework proposed for biostratinomic classification integrated genetic relationships in ternary diagrams, absence of respective spatiotemporal elements constrains comprehensive interpretations of textural origins. This lack of integration in aspects of genetic and spatiotemporal dynamics renders somewhat disconnected, many direct and indirect relationships between processes and fabrics, and subsequent textural changes in carbonate diagenesis.

A NEW INTEGRATED CONCEPTUAL MODEL

An holistic approach to conceptual modelling of texture genesis and diagenesis facilitated erection of integrated frameworks, useful for interpretations of linkages in evolutionary dynamics. The proposed model consists of conceptual frameworks for genetically-significant fabrics and respective spatiotemporal relationships. However, the problem arose on integration of paleobiologically-significant fabrics into conceptual frameworks, in the absence of a genetic classification scheme. To rectify this, we proposed a genetic classification scheme for bioturbate textural heterogeneities (Keswani *et al.*, 1995). Since the proposed classes of paleoecologically-significant burrow fabrics and bioturbate textures manifested effects of biotic processes, integration of these elements into an evolutionary model facilitated construction of genetic and spatiotemporal frameworks. Thus, interpretations regarding the nature of intrinsic controls on texture genesis are derived from understanding correlative relationships in unique and overlapped spatiotemporal dimensions, associated with paleoecological-geochemical characteristics in constituent fabrics.

This model represents fabrics and textural relationships as products of inherently-linked genetic and spatiotemporal dynamics. Such a dynamic model integrates texture genesis and diagenesis through analysis of genetically-significant fabrics, and correlation of respective spatiotemporal elements. These elements include both unique and overlapped spatiotemporal dimensions associated with fabric genesis. Correlation of such elements on genetically-significant scales provide insights on direct interplays and indirect feedback interactions in texture genesis and diagenesis. The concept of genetic linkages between contemporaneous and evolutionary-scale processes that influenced fabric origins, form the basis of our model. Therefore, the proposed model provides a unified framework for understanding the relationships between bioturbation and carbonate diagenesis.

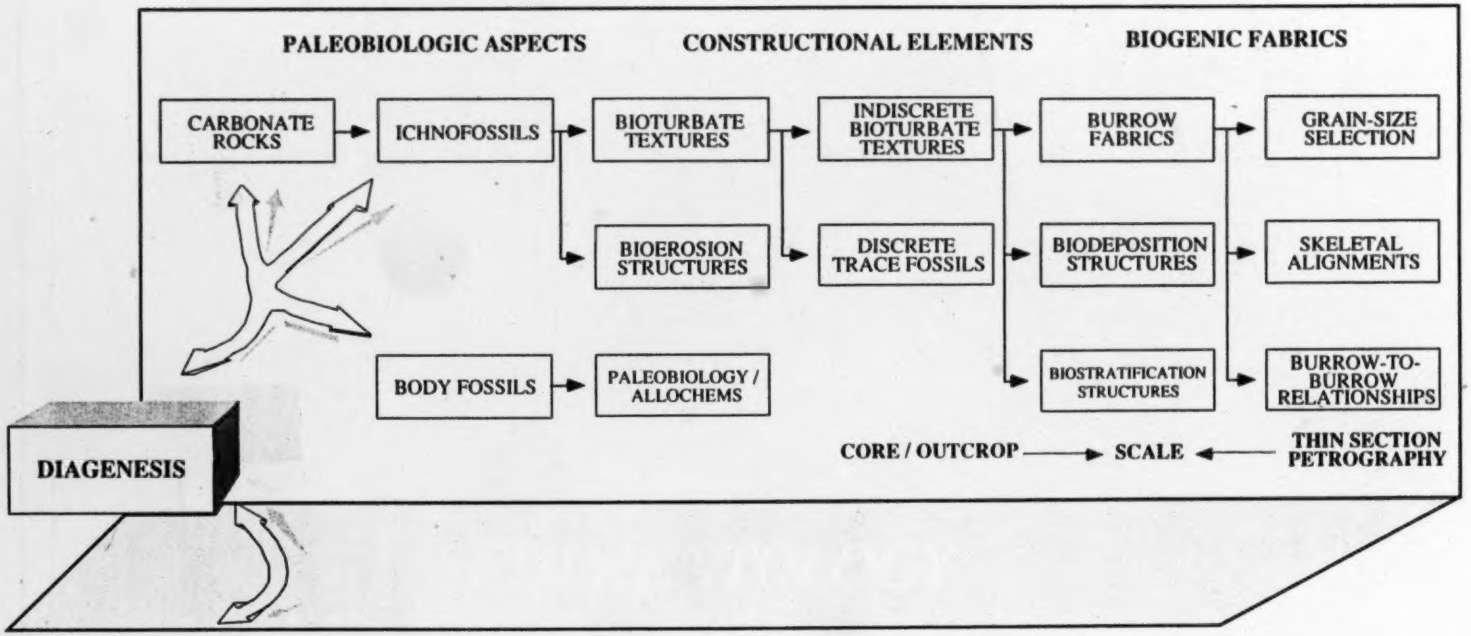
Textural relationships that showed recurrent associations between genetically-significant fabrics within particular sedimentary environments reflect "snapshots" of direct interplays and feedback effects in textural evolution. Genetic classification of textural parameters, particularly those derived through bioturbation and geochemical reactions represent an initial step toward understanding the nature of paleobiological controls on diagenetic fabrics. Since these parameters reflect the cummulative effects of processes and spatiotemporal scales, our model forges linkages between fabrics developed both synchronously and diachronously. Thus, applications of our model in textural analysis provides a vehicle for understanding paleobiological controls on diagenetic fabrics.

GENETIC FRAMEWORK

Textural relationships in detrital carbonate deposits are produced from interactions of biological, sedimentological and geochemical processes, which functioned on both synchronous and diachronous temporal spans (Bathurst, 1975; Fursich, 1978; Kidwell *et* *al.*, 1986; Scoffin, 1987; Tucker and Wright, 1990; Choquette and James, 1990, Boudreau 1997). These genetic aspects have been depicted as integrated three-dimensional natural systems, where dynamic interactions between processes affected textural developments that influenced early- and late-diagenetic regimes. This three-dimensional framework consists of axes for respective textural products generated in paleoecological-geochemical dynamics (Figure 1). Such a systematic arrangement of fabrics in our framework depicts textural relationships as inseparable genetic entities, where boundary conditions for intrinsic controls on substrate evolution have been defined by the nature of direct interplays and indirect feedback interactions. Although Frey (1973), Frey and Pemberton (1984, 1985), Frey and Wheatcroft (1989) and Pemberton *et al.* (1992) summarized major relationships among biogenic structures, the proposed framework integrates Keswani *et al.*'s (1995) spectrum of petrographically-identifiable classes of indiscrete bioturbate textures. Such genetic classes of burrow fabrics and discrete trace fossils formed collectively, the constructional elements of the biologic axis in our genetic framework.

Genetic aspects of carbonate sedimentology and diagenesis have been summarized extensively in the geologic literature. These include works on origins and applications of sedimentologic and diagenetic fabrics and textural relationships in carbonate deposits at both shallow- and deep-burial environments (Dunham, 1962; Embry and Klovan, 1971; Bathurst, 1975, 1980, 1984, 1985, 1987; Buxton and Sibley, 1981; Flugel, 1982; Shinn and Robbin, 1983; Scholle and Halley, 1985; Scoffin, 1987; Moore, 1989; Choquette and James, 1990; Tucker and Bathurst, 1990; Tucker and Wright, 1990; Blanchon, 1992; Pedley, 1992; Demicco and Hardie, 1994; Clari and Martire, 1996). In the proposed framework, such fabrics and textural relationships comprise the constructional elements of respective sedimentary and diagenetic axes. Taphonomic signatures associated with these skeletal deposits have been classified genetically, in a biostratinomic scheme (Kidwell *et al.*, 1986). Since these preservational processes represent aspects of texture genesis, emplacements of taphonomic elements in our conceptual framework is somewhat ambiguous. Accordingly, such taphonomic aspects have been conceptualized as straddling the points of intersections on the axes, which represented genetic interplays within this

Figure 1. Three-Dimensional Conceptual Framework For Texture Genesis in Ancient Detrital Carbonate Deposits. Fabrics Generated by Respective Processes Represented on Paleobiologic, Sedimentologic and Diagenetic Axes. Depiction of Relationships Among Paleobiologic Aspects and Scales.



three-dimensional framework. These genetic focal points, overlaps in axial relationships and associated spatiotemporal elements, suggest that characteristics of textural relationships manifest aspects of fabric evolutionary dynamics that influenced origins of taphonomic signatures.

SPATIOTEMPORAL FRAMEWORK

Spatiotemporal elements represent integral aspects of physical and mineralogical characteristics manifest in textural relationships of ancient detrital carbonate deposits. These characteristics reflect spatiotemporal dynamics associated with direct interplays and indirect feedback interactions in textural evolution. Such relationships have been depicted as unique and overlapped temporal spans, and spatial scales (Figure 2). Two disinct temporal scales with both unique and overlapped genetic intervals have been recognized in textural relationships produced by paleoecological-geochemical dynamics: (1) biologically-sedimentologically-, and (2) diagenetically-significant spans. These temporal spans are associated with processes that functioned on local and regional spatial scales, respectively. Hence, the correlations proposed in this conceptual framework show physiogenic and biogenic processes affected the development of diagenetic fabrics in textural evolutionary dynamics.

The correlations in spatiotemporal dimensions showed successive fabric developments influenced the nature of controls on textural evolution, particularly origins and distribution patterns among diagenetic fabrics. This concept of genetic linkages in relationships among spatiotemporal scales implies that contemporaneous physiogenic and biogenic fabrics affected both early- and late-diagenesis. Accordingly, both physiogenic and biogenic fabrics represented controls on diagenetic mechanisms that produced integrated synchronous and diachronous relationships. Furthermore, these genetic linkages coupled effects of local- and regional-scale processes, respectively. Since our spatiotemporal framework established genetic linkages in such relationships, it facilitates interpretations of textural evolution associated with the progressive burial of substrates from surface to subsurface environments. Thus, our framework integrates textural characteristics and distribution patterns in diagenetic relationships.

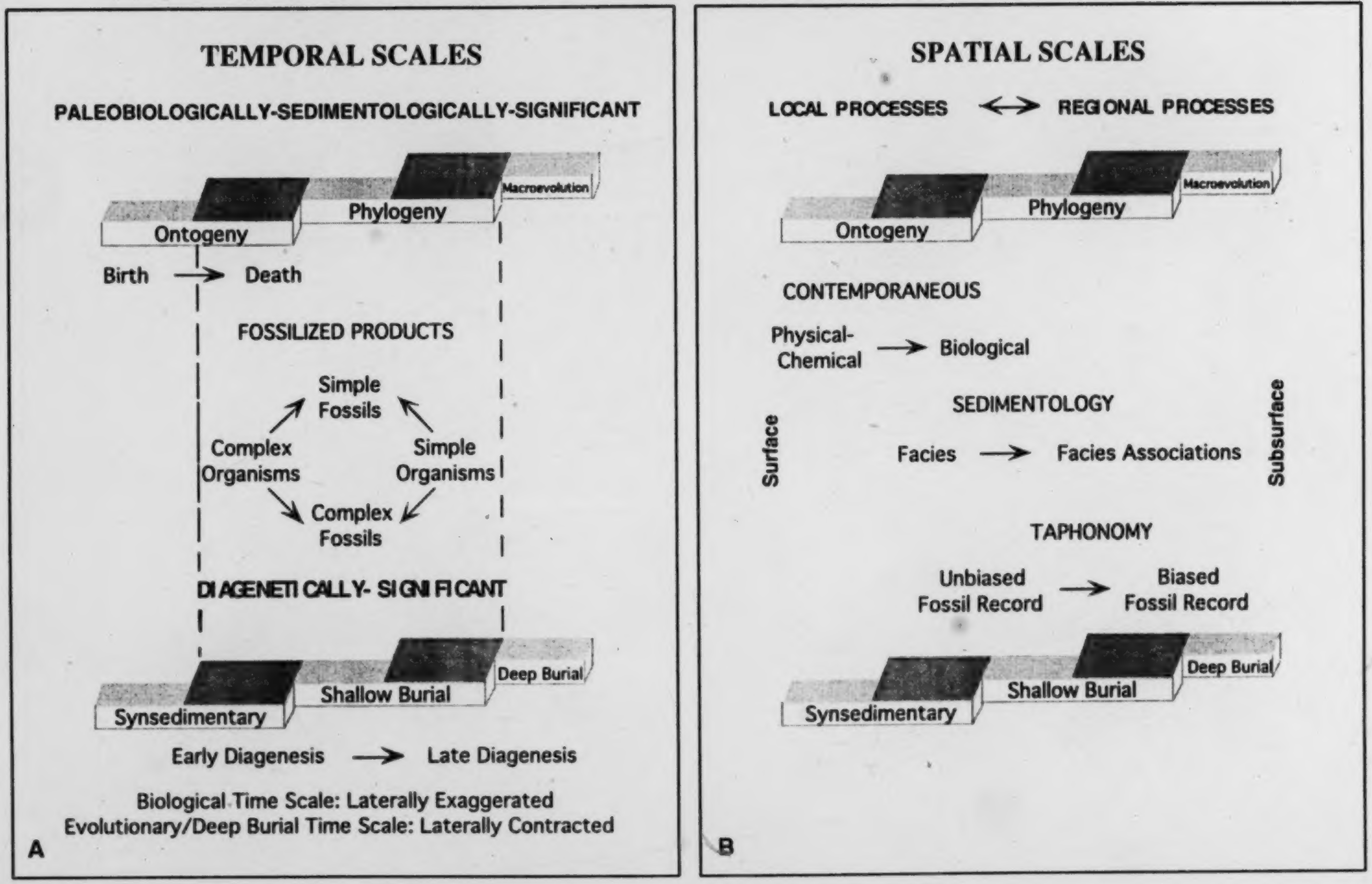
Temporal Scales (A)

Temporal relationships manifested inherently in genetically-significant fabrics and textures have been illustrated in the proposed framework (Figure 2A). These include two succinct temporal scales: (1) biologically-sedimentologically-significant, and (2) diagenetically-significant spans. Correlations of temporal ranges associated with genetically-significant fabrics including contemporaneous and succeeding spans, establishes linkages in textural evolutionary dynamics by demarcating chronologic relationships and overlaps. These relationships in temporal dynamics represent mutually independent, yet genetically-linked associations related to fabric evolution. Thus, unique and overlapped temporal relationships depicted in the genetically-significant spans, show fabric evolutionary dynamics include both direct interplays, and indirect feedback effects. Such complex temporal relationships include diachroneities between biological-sedimentological texture genesis and development of non-synsedimentary early- and late-diagenetic fabrics. For illustration purposes, these spans have been presented in laterally-exaggerated, and contracted bar-scales, respectively (Figure 2) .

Paleoecological dynamics and morphological evolution represent aspects of biologically-significant temporal relationships. These represent inseparable genetic elements that influenced characteristics of textural developments. Temporal scales have been delineated through analysis of distribution patterns in both body and trace fossil records (Seilacher, 1977, 1986; Stanley, 1977; Sepkoski, 1981, 1990, 1991, 1992; Sepkoski *et al.*, 1981; Boucot, 1983, 1990; Bottjer *et al.*, 1988, 1995; Miller and Sepkoski, 1988; Cornell and Lawton, 1992; Ricklefs and Schluter, 1993; Valentine and Jablonski, 1993; Bottjer and Droser, 1994; Jablonski and Sepkoski, 1996).

The proposed framework for temporal relationships integrates scales associated with non-equivalent paleobiological entities. These paleobiological entities have been characterized morphologically in descriptive terms, such as simple and complex fossil

Figure 2. (A) Relationships Between Paleobiologically-Sedimentologically-Significant, and Diagenetically-Significant Spatiotemporal Scales. Overlaps (dashed lines, darker shaded) in Scales are Indicative of Interplays Among Biologic, Sedimentologic, and Diagenetic Processes and Feedback Dymamics in Textural Evolution. (B) Spatiotemporal Relationships in Genetically-Significant Scales Depicted in Figure 2A.


TEMPORAL SCALES
PALEOBIOLOGICALLY-SEDIMENTOLOGICALLY-SIGNIFICANT
Ontogeny
Phylogeny
Macroevolution
Birth → Death
FOSSILIZED PRODUCTS
Simple Fossils
Complex Organisms
Simple Organisms
Complex Fossils
DIAGENETICALLY-SIGNIFICANT
Synsedimentary
Shallow Burial
Deep Burial
Early Diagenesis → Late Diagenesis
Biological Time Scale: Laterally Exaggerated
Evolutionary/Deep Burial Time Scale: Laterally Contracted
A
SPATIAL SCALES
LOCAL PROCESSES ↔ REGIONAL PROCESSES
Ontogeny
Phylogeny
Macroevolution
CONTEMPORANEOUS
Physical-Chemical → Biological
SEDIMENTOLOGY
Surface
Facies → Facies Associations
Subsurface
TAPHONOMY
Unbiased Fossil Record → Biased Fossil Record
Synsedimentary
Shallow Burial
Deep Burial
B

forms for both the skeletal and ichnologic components of the paleontological record. Morphologically-simple and -complex organisms produce both simple and complex, body and trace fossil records (Bromley, 1990; 1996). This characterization of paleobiologic disequilibrium in the paleontologic record manifests temporal dynamics associated with trends in both phylogenetic and macroevolutionary hierarchies and in paleoecological versatility patterns in marine benthic paleocommunities (Wilson, 1975; Scott, 1976; Sepkoski *et al.*, 1981; Boucot, 1983, 1990; Minkoff, 1983; Vermeij, 1987; Bottjer *et al.*, 1988, 1995; Miller and Sepkoski, 1988; McNamara, 1990; Sepkoski, 1990, 1991, 1992; Valentine and Jablonski, 1993; MacNally, 1995; Jablonski and Sepkoski, 1996; Bambach and Bennington, 1996).

Textural developments manifest complex temporal dynamics, including diachronous relationships of various scales. The large-scale diachroneities define the temporal ranges that separate both biologically- and sedimentologically-significant scales from diagenetically-significant spans in texture genesis. However, small-scale diachroneities represent aspects of both of these spans. Such complex relationships in temporal dynamics are apparent in comparisons of spans manifested in the development of paleobiologically-influenced textures. Fabrics within these relationships showed the cumulative effects of contemporaneous biological-sedimentological processes, and associated early-diagenesis in both depositional and shallow burial environments, and effects of late-diagenesis in deep subsurface zones. For example, comparisons of temporal spans associated with early-diagenetic processes in shallow burial anoxic environments have been estimated at 2000-3000 years (Canfield *et al.*, 1996). Comparatively, biologically-significant temporal scales range from milliseconds to thousands, and millions of years, and correlations of these to diagenetically-related spans show diachronous relationships (Foster *et al.*, 1990). Spatial dimensions associated with processes that influenced textural developments range from 10^6 to 10^{14} square meters (Foster *et al.*, 1990).

Spatial Scales (B)

Spatial scales represent aspects of physiogenic, biogenic and diagenetic processes. Aspects of these scales have been recorded in genetic elements, manifested in both the physical and mineralogical characteristics of textural developments. Such spatial dimensions represent aspects of genetic relationships in the conceptual framework proposed. These dimensions are represented as local and regional scales. A two-way arrow between these local- and regional-scales indicates reciprocal influences among processes associated with respective spatial dimensions (Figure 2B).

The proposed framework links spatial scales in genetic relationships among both stratigraphic and sedimentologic units. These scales correlate stratigraphically to textural units in surface and subsurface intervals, and sedimentologically to facies and facies associations. The spatial overlaps shown in our diagrams link areas where genetic interplays between contemporaneous ecological dynamics and late-diagenesis influence textural evolution. Therefore, our integrated framework shows that textural parameters reflect constraints on both genetic and temporal dynamics in fabric evolution.

Most sedimentologic and diagenetic models provide scales for spatial dimensions in both modern and ancient detrital carbonate depositional systems (Wilson, 1975; Bathurst, 1975; James, 1984; Harris, 1985; Moore, 1985, 1989; Bathurst and Land, 1986; Scoffin, 1987; Choquette and James, 1990; Tucker and Bathurst, 1990; Coniglio and Dix, 1992; Jones and Desrochers, 1992, Boudreau, 1997). These summaries focused mainly on genetic relationships among physical and geochemical processes that defined facies characteristics. However, such works have underscored the significance of biotic interactions in texture genesis, which influences carbonate sedimentology and diagenesis.

Yet, carbonate depositional environments represent complex ecosystems, where biotic processes comprise elements of genetic relationships in platform construction. Spatial boundary conditions in ecological dynamics affect the nature of biotic processes in both modern and ancient environments (Fox and Morrow, 1981; Ricklefs, 1987; Foster *et al.*, 1990; Cornell and Lawton, 1992; Ricklefs and Schluter, 1993; Bascompte and Sole, 1995 a,b, 1998a,b; Brown *et al.*, 1995; Rohani and Ruxton, 1995; Ruxton, 1996;

Jablonski and Sepkoski, 1996; Rohani *et al.*, 1997; Cohen, 1998). Consequently, these interactions influence the range and distribution patterns among textural relationships which define facies characteristics and associated diagenetic regimes. Therefore, analysis of spatial parameters for biotic processes provide data useful for interpretations of interactions that influence both texture genesis and diagenesis.

Taphonomy

Developments of textural relationships and taphonomic signatures represent inseparable genetic entities in ancient detrital carbonate deposits. Genetic interplays in surface and subsurface paleoenvironments, influence both textural evolution and fossilization of skeletons. These fossilization processes included physiogenic, biogenic, and diagenetic mechanisms, which modify textural relationships and transformed skeletal accumulations into taphonomic entities with characteristic signatures (Fursich, 1978; Kidwell and Jablonski, 1983; Brett and Baird, 1986; Kidwell *et al.*, 1986; Kidwell, 1991; Kidwell and Behrensmeyer, 1993; Kidwell and Flessa, 1995). Since these processes represent genetic analogs in both taphonomy and textural origins, fossilization aspects constituted integral elements of proposed conceptual frameworks. Thus, taphonomic elements have been modelled conceptually as both genetic and spatiotemporal equivalents to aspects of textural origins (Figure 2B). Our frameworks depicted these textural elements as taphonomically-significant entities. This concept facilitates interpretations of taphonomic processes that are inherent in textural characteristics. Hence, a genetic approach provides a useful tool in understanding origins of the preservational attributes of paleontological records (Scott, 1976; Valentine, 1990; Kidwell and Flessa, 1995; Jablonski and Sepkoski, 1996).

The conceptual model proposed in this paper accounts for many preservational biases incorporated in textural relationships in different paleoenvironments. Since physical and mineralogical parameters manifest effects of genetic and spatiotemporal dynamics, these attributes also represent coeval taphonomic products. Such preservational elements reflect biases incorporated at respective stages of textural evolution in progressive burial of the substrate. Therefore, analogous relationships in both textural and taphonomic elements have been modelled spatiotemporally, in pre- and post-burial domains.

DISCUSSION

Traditionally, studies focused on the concept of textural evolution erected mostly separate paragenetic models for both early- and late-stage diagenesis. These interpretations lacked cohesion, particularly in regard to development of a comprehensive model for textural evolution, where biological parameters may represent an intrinsic control on diagenesis associated with progressive burial. For example, recent petrographic and SEM studies on origins of early diagenetic textures alluded to biogenic influences on fabric origins (Jones, 1992, 1995; Jones *et al.*, 1997; Webb *et al.*, 1998). Alternatively, some geochemical and textural studies omitted altogether, the effects of bioturbation on carbonate diagenesis (Montanez and Read, 1992; Choquette *et al.*, 1992; Kupecz and Land, 1994; Chafetz and Rush, 1995). Yet, studies focused on early-diagenesis in bioturbated substrates of modern environments have shown effects of organism-sediment interactions include modifications to both physical and geochemical parameters (Warme, 1967; Nichols, 1974; Hylleberg, 1975; Myers, 1977; Berner, 1980; Tevsz *et al.*, 1980; Carney, 1981; Aller, 1982, 1984; Rhoads and Boyer, 1982; Ray and Aller, 1985; Meldahl, 1987; Barnes and Hughes, 1988; Wanless *et al.*, 1988; Jumars *et al.*, 1990; Tevesz *et al.*, 1990; Whaetcroft *et al.*, 1990; Amon and Herndl, 1991; Pedley, 1992; Wanless and Tedesco, 1993; Yager *et al.*, 1993; Soetaert *et al.*, 1996; Ziebis *et al.*, 1996, Boudreau, 1997). These contemporaneous changes to substrate parameters likely represent inseparable controls on subsequent diagenetic processes. Although many studies have suggested the early effects of bioturbation, a comprehensive understanding of fabric genesis in textural evolution remains unclear.

To rectify the problem of genetic disconnection in previous studies, our paper has proposed an integrated conceptual model for texture genesis and diagenesis. The conceptual frameworks proposed in this model correlate both unique and overlapping spatiotemporal relationships among genetically-significant elements in both the physical and mineralogical characteristics of constructional fabrics. These correlations link genetically, the respective stages in textural evolution. Such an holistic concept integrates contemporaneously-produced, discrete and indiscrete aspects of bioturbate textures, and origins of sedimentary and diagenetic fabrics in an evolutionary paradigm.

Since bioturbation generates both discrete trace fossils and indiscrete textures, these products represent intrinsic paleobiological controls on diagenesis. Integration of both these aspects of bioturbate textures in an holistic model prompts extension of the genetic concepts inherent in Seilacher's (1964, 1967a) ichnofacies, to classification and applications of schemes for indiscrete burrow fabrics. Accordingly, diagenetic fabrics associated with ichnofossils, and classes of indiscrete bioturbate textures have been regarded as inseparable genetic entities. An understanding of these paleobiological processes and inherent linkages to diagenetic textures will likely provide insights on the effects of paleoecological dynamics on dolomitization and on hydrocarbon distribution. Thus, our conceptual model provides a framework for understanding the nature of relationships in paleobiological-geochemical dynamics.

The correlations in the proposed new model established cohesiveness among genetic elements, and respective spatiotemporal relationships manifest in fabrics generated by paleoecological-geochemical dynamics at various scales. These relationships include effects of both contemporaneous sedimentological-paleobiological processes and relevant early-diagenesis, and late-diagenesis associated with progressive burial of substrates. Such an integrated model for textural evolution links the effects of both direct and indirect genetic interplays, and respective spatiotemporal elements. Integration of these elements in a conceptual model provides an interpretive tool useful for understanding the nature of fabric evolution in textural developments, and particularly the genetic linkages inherent among the effects of paleobiological processes and carbonate diagenesis.

To understand intrinsic relationships between sedimentologic, paleobiologic and diagenetic processes, and the cumulative effects on textural characteristics and on taphonomic signatures, consider the example of oxygen-depleted paleoenvironments. Most reconstructions of such low-oxygenated paleoenvironments have been based predominantly on sedimentological studies (Calvert, 1966; Demaison and Moore, 1980; Edwards, 1985; Oschmann, 1988; Pedersen and Calvert, 1990; Wignall, 1991a; Allison *et al.*, 1995; Emery and Myers, 1996). Characteristic ichnological signatures have been recorded in these substrates (Bromley and Ekdale, 1984; Savrda *et al.*, 1984; Ekdale, 1985; Savrda and Bottjer, 1986, 1987, 1989, 1991; Ekdale and Mason, 1988; Föllmi and Grimm, 1990; Wignall, 1991b, 1993; Savrda, 1992, 1995; Savrda and Sageman 1994). But, applications of the new conceptual model proposed in this paper show genetic relationships among various aspects of reduced-oxygen settings. Many sedimentological and ichnological studies omit or allude to the notion that reduced-oxygenated substrates also represent unique diagenetic environments. Allison (1988) and Briggs *et al.* (1996) noted the intrinsic relationships between taphonomy and diagenesis. Although some studies have been focused on organic geochemistry and taphonomy, the nature of feedback dynamics between these processses, and the roles of bioturbation in texture genesis remains somewhat unclear. However, utilization of the proposed frameworks show that paleobiological processes, or the lack of these (in some oxygen-depleted substrates), and respective feedback dynamics influence the development of sedimentologic, diagenetic and taphonomic signatures. Although high biotic density patterns have been documented locally, the relative inhospitable conditions in such substrates limited trace fossil diversity (Rhoads and Morse, 1971; Demaison and Moore, 1980; Bromley and Ekdale, 1984; Edwards 1985; Raiswell *et al.*, 1987; Oschmann, 1988, 1993; Föllmi and Grimm, 1990; Wignall, 1991b, 19993; Allison *et al.*, 1995). These relatively reduced diversity patterns influenced in part, the persistence of low-oxygen conditions, which generated both unique diagenetic, and exceptional taphonomic regimes (Zangerl, 1971; Curtis, 1980; Ekdale *et al.*, 1984; Seilacher *et al.*, 1985; Reading, 1986; Plotnick, 1986; Raiswell *et al.*, 1987; Allison, 1988; Bromley, 1990, 1996; Allison *et al.*, 1995; Briggs *et al.*, 1996; Canfield *et al.*, 1996; Wilkin and Barnes, 1997). Hence, application of the conceptual model show paleoecological dynamics constrained the inseparable genetic relationships between diagenesis and taphonomy.

Alternatively, the use of our new conceptual model showed contemporaneous paleoecological responses represent merely a part of the paleobiologically-significant temporal scales that constrained mechanisms in diagenesis. These constraints included temporal elements associated with organic evolution, and differential paleoecological responses (Seilacher 1986; Plotnick, 1986; Droser, 1987; Bottjer *et al.*, 1988, 1995; Droser and Bottjer, 1989, 1992, 1993; Sepkoski, 1991; Bottjer and Droser, 1992, 1994). Such evolutionary paleoecological responses influenced in part, both texture genesis and preservation potential (Plotnick, 1986). Both these controls have been linked in correlations of synchronous and diachronous relationships. Thus, genetic interplays and feedback dynamics associated with stages of biological evolution and respective paleoecological interactions, represent inherent temporal constraints on diagenesis and taphonomy. Since occlusional effects of both these processes limited genetic information, applications of our conceptual framework to fragmentary textural data sets provided insights on mere spatiotemporally-restricted, paleobiological controls.

Furthermore, utilization of our conceptual frameworks provide insights on possible paleoecological constraints in secular variations of dolomite textures. Sibley (1991) suggested changes in physical or chemical conditions as possible mechanisms that produced these secular variations in dolomites. Alternatively, we suggest a possible biological evolutionary cause for such textural changes. Since both morphological and behavioural evolution influenced trophic strategies in paleoecological responses to both physical and chemical conditions, changes in the nature of organism-substrate interactions likely influenced locally and at facies-scales diagenetic textural origins (Figures 3,4). Consequently, these genetic relationships imply that diagenetic signatures such as secular variations in dolomite fabrics manifest possible paleobiologically-significant temporal ranges that excede those determined merely by geochemical analysis. The possibility of such evolutionary biological controls reflecting secular changes in dolomite fabrics requires further investigation.

Following several decades of economically-driven research, the "dolomite problem" has remained largely unresolved. Typically, most diagenetic studies have disregarded a fundamental tenet: carbonate build-ups represent essentially paleobiological constructions that formed through aggradation of organically-derived sediments, and subjected to physiogenic, biogenic and diagenetic processes (Bathurst, 1975; Scoffin, 1987, Tucker and Wright, 1990). These studies have been focused primarily on geochemical approaches to understanding dolomitization. Consequently, previous models constructed for dolomitization mechanisms have been based on somewhat fragmentary data sets; and these applied merely to particular carbonate paleoenvironments. This approach to understanding carbonate diagenesis has resulted in many proposals for modelling dolomitization locally; but these lacked genetic comprehensiveness. Such limitations in geochemical models stem in part, from the absence of a conceptual foundation that integrates both genetic and spatiotemporal elements associated with paleoecological-geochemical dynamics in textural evolution.

Yet, fabric-selective dolomites in burrow fills have been documented commonly in many studies of ancient carbonate deposits (Beales, 1953; Murray and Lucia, 1967; Buchbinder and Friedman, 1970; Bathurst, 1975; Kendall, 1977; Morrow, 1978; Jones *et. al.*, 1979; Choquette and Steinen, 1980; Narbonne, 1984; Pickerill *et. al.*, 1984; Bathurst and Land, 1986; Theriault and Hutcheon, 1987; Banner *et. al.*, 1988; Cander *et. al.*, 1988; Chow, 1991; Chow and Longstaffe, 1995). The signficance of these dolomite fabrics may have been underestimated. Such dolomite fabrics (Figures 3,4) form a part of a spectrum of paleobiologically-influenced diagenetic textures (Keswani and Pemberton, 1997, 1998). But, the holistic approach to construction of an integrated conceptual model for textural evolution provides a comprehensive foundation for future research on carbonate diagenesis. Applications of this model will likely provide data useful for understanding the nature of paleobiological controls on dolomitization (Keswani and Pemberton, 1997, 1998).

Analysis of physical and mineralogical characteristics of textural relationships, and emplacement of spatiotemporal elements in the proposed framework provides data on origins, and subsequent changes in fabrics by carbonate diagenesis. Applications of this framework are useful for interpretations of the effects of contemporaneous biotic processes and feedback interactions on both early- and late-stage diagenesis. These links in genetic

Figure 3. Standard thin-sections show variations in paleobiologically-influenced diagenetic textures within the Mississippian Midale carbonates, Williston Basin, Saskatchewan. (A,B) Textural relationships and diagenetic associations include dolomites in local heterogeneities such as the fills of clustered interpenetrating fabrics and homogenized substrates. These textural relationships defined the bioturbation-derived skeletal dolowackestone at well 7-1-5-19W2, (A) depth 1717.72 m and (B) depth 1708.99 m. The overlapped relationships among the wall structures of distinct burrow fabrics (arrows) and the reworked host substrates show local variations in associated diagenetic fabrics. The sharply- defined wall structures of these distinct burrow fabrics consist of microfills that show an association with light gray-colored dolomite. Since bioturbate textures are associated with dolomite fabrics in both the burrow fills and host substrates, these suggest an inherent relationships between microfills and diagenesis; and paleobiological controls at both local and textural facies scales. These paleobiologically-influenced dolomites likely developed by burrow fabric amalgamation, and selective dolomitization of the clustered interpenetrating and homogenized bioturbate textures. (C) A thin-section cut at well 12-24-3-20W2, depth 6262.56 ft. shows an upper part that consists of a skeletal packstone which grades downward into a skeletal dolowackestone. These variations are defined by the development of paleobiologically-influenced diagenetic fabrics, associated with clustered non-interpenetrating and homogenized bioturbate textures. Fabric-selective dolomite associated with microfills in the distinct burrows, defined local heterogeneities in this texture. Dolomitization of the micrite within these heterogeneities and the host substrates suggest that bioturbation-derived textural controls, particularly the variations in the amounts matrix- and grain-supported relationships influenced diagenesis, at both local and facies-scales. (D) A bioturbation-derived skeletal wackestone shows local textural variations from mudstone to packstone at well 7-1-5-19W2, depth 1721.76 m. These local textural heterogeneities consist of burrow fabrics defined by grain-size contrasts between the fills and the host substrates, preferred alignments of allochems and their morphological characteristics, and by the burrow-to-burrow relationships. These bioturbate textures show mostly a homogenized substrate with preservation of vestiges of clustered interpenetrating fabrics, locally. The physical characteristics of these fabrics coupled with their inherent relationships to dolomite textures provide insights on the complexities of genetic linkages between contemporaneous paleobiological processes and both early- and late-stage diagenesis. Consider the two distinct burrow fabrics defined by microfills (arrows). Although both these fabrics consist of microfills, they are characterized by unlike diagenetic signatures. The burrow fabric indicated in the lower part of the thin-section shows planar alignment of allochems and microfills that have remained undolomitized. Yet, the burrow indicated in the middle part of this thin-section shows a lack of a preferred orientation in skeletal fragments, and microfills associated with fabric selective-dolomite (d). The physical and mineralogical characteristics of these textures suggest that such genetic classes of burrow fabrics are probably generated by unlike processes. These contrasts in fabrics suggest that dissimilar biotic processes differentially influenced texture genesis and diagenesis. A comparison of thin sections B, C and D show differences in the effects of bioturbation on dolomitization in substrates comprised of similar textural relationships. Application of the conceptual frameworks suggest intrinsic controls in paleoecological-geochemical dynamics. Therefore, local variations in diagenetic fabrics likely reflect differences in the nature of biotic processes and their impact on geochemical regimes, particularly on the mechanisms of dolomitization.

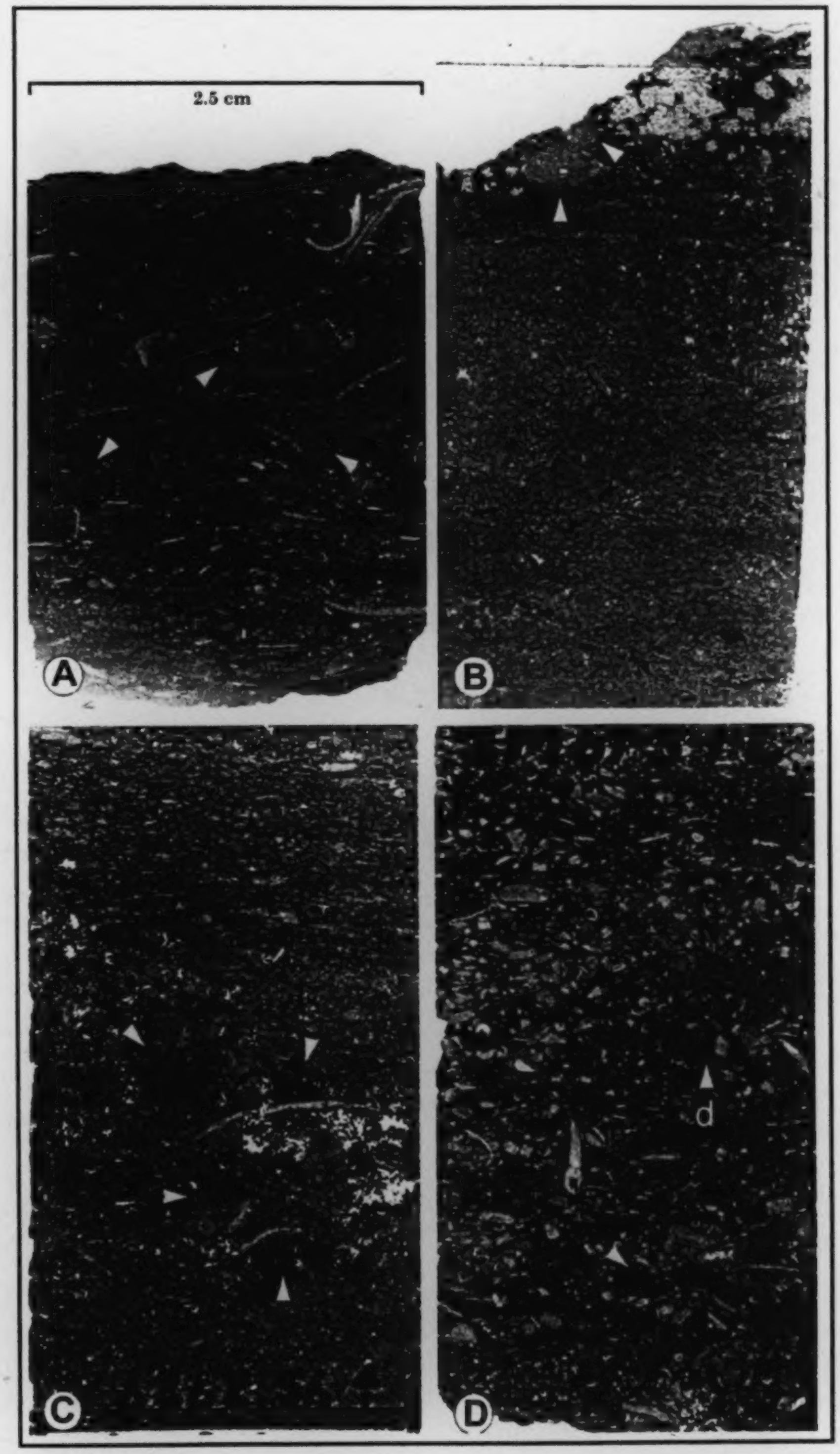
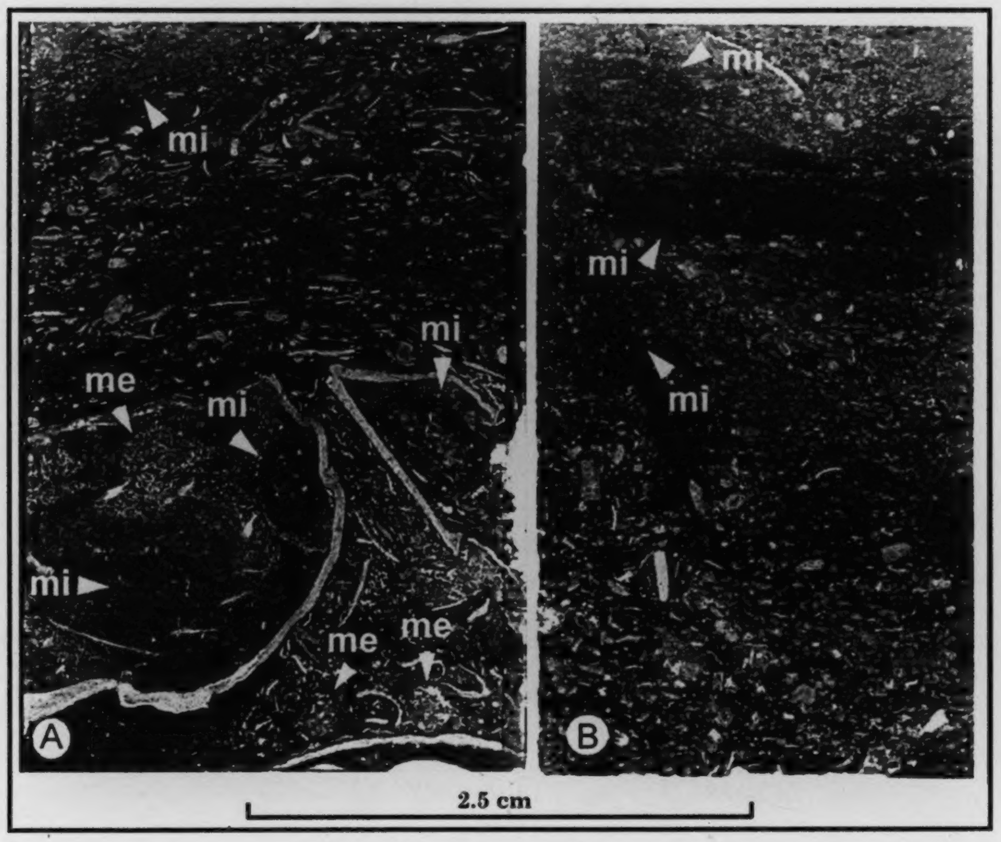

2.5 cm
A
B
C
D
d

Figure 4. Standard thin-sections show skeletal dolowackestones characterized by textural heterogeneities that consist of distinct, genetically-significant fabrics developed at well 12-24-3-20W2, depths (A) 6184.4 ft, and (B) 6287.1 ft in the Midale carbonates, Williston Basin, Saskatchewan. These textural relationships show variations from dolomudstone to dolopackstone, locally. (A) Dolowackestone shows distinct genetically-significant fabrics: the upper part of this thin-section shows mainly a diagenetic laminae defined by both the alignment of allochems and incipient solution seams which developed parallel to the bedding; and the lower part of this thin section shows predominantly biogenic fabrics defined by microfills (mi) and mesofills (me). Although the overall fabric in the upper part of this thin-section has been produced by compaction, vestiges of microfills within the compressed burrow fabric (arrow) remains preserved. The burrow fabrics in the lower portion of the thin-section shows a clustered non-interpenetrating burrow-to-burrow relationship. The microfills within these bioturbate textures and the fabric-selective dolomites associated with distinct burrows suggest that the effects of microphagous processes represent an important control on diagenesis. (B) A bioturbation-derived skeletal dolowackestone consists of local textural variations from dolomudstone to dolopackstone. These heterogeneities define burrow fabrics comprised of microfills and their burrow-to-burrow relationships show both clustered interpenetrating patterns and homogenized bioturbate textures. Such distinct burrow fabrics showed both microfills (mi) associated with planar alignment of allochems, and those devoid of a preferred orientation. Both these burrow fabrics may have been generated by similar biotic processes, and the textural and morphological differences are simply a function of the thin-section orientation. These microfills show fabric-selective dolomites, which indicates that microphagy and alternate bioturbation processes that generated matrix-supported relationships, enhanced the development of paleobiologically-influenced diagenetic textures.


mi
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2.5 cm

interplays include diachroneities that influence fabric origins, and distribution patterns in the spectrum of paleobiologically-influenced diagenetic textures. Thus, applications of this conceptual model in textural analysis showed genetic classes of burrow fabrics likely influenced differentially, mechanisms of dolomitization (Keswani and Pemberton, 1997).

Selectivity in dolomitized burrow fills suggest inherent paleobiological controls and feedback dynamics in carbonate diagenesis. These associative relationships indicate bioturbate textural changes and geochemical modifications created conditions that favoured dolomitization (Figures 3,4). Overlaps in the correlation of spatiotemporal relationships associated with both bioturbation and dolomitization showed biotic processes impacted somewhat, the nature of geochemical mechanisms. This approach provides data consistent with previous geochemical interpretations, which modelled paleobiologically-influenced dolomite fabrics as products of both early- and late-stage diagenesis (Kendall, 1977; Morrow, 1978; Jones *et. al.*, 1979; Pickerill *et. al.*, 1984; Chow, 1991; Chow and Longstaffe, 1995). Many preceding studies suggested that organism-sediment interactions enhanced locally, substrate permeability characteristics, which provided conduits for migration of dolomitizing fluids (Beales, 1953; Kendall, 1977; Morrow, 1978; Jones *et. al.*, 1979; Narbonne, 1984; Pickerill *et. al.*, 1984; Chow, 1991; Tedesco and Wanless, 1991; Chow and Longstaffe, 1995; Keswani and Pemberton, 1997). But, the mechanisms of these intrinsic paleobiological controls that influenced textural origins, and spatial distribution patterns in dolomite fabrics remains unclear.

The new model provides a conceptual foundation for future investigations on paleobiological controls in diagenesis. This paleobiological perspective offers opportunities for research focused on understanding genetic relationships in mechanisms of dolomitization. Such research could be directed on two tracks: (1) investigations on the relationships between specific burrow fabrics and the development of dolomite textures; and (2) studies centered on comparisons of these diagenetic relationships in various carbonate facies and different stratigraphic settings. Such comparative studies provide insights on the roles of evolutionary biotic processes in origins of diagenetic textures, and on our understanding of both spatial and temporal variability in distribution patterns of paleobiologicaly-influenced dolomites. This approach will likely provide data useful for interpretations of paleobiological influences on secular changes and abundance patterns in dolomite fabrics. These variations have been interpreted in non-paleobiological paradigms (Sibley, 1991; Given and Wilkinson, 1987). Applications of data on such spatiotemporal variability patterns in distributions of paleobiologically-influenced dolomites will likely advance our understanding of evolutionary controls on diagenesis.

This approach provides an improved understanding of the effects of specific paleoecological interactions and feedback dynamics in textural evolution, and contributes toward an understanding of secular variations in the development of dolomite fabrics. For example, consider the unique spatiotemporal relationships in the genetic elements of selectively dolomitized burrow fills. Keswani and Pemberton (1993, 1997, 1998) and Keswani *et al.*, (1995) documented that local textural heterogeneities showed dolomite associated with microfills, which sharply defined the wall-structures of distinct burrow fabrics (Figures 2,3). Our conceptual model showed these local textural heterogeneities manifest diachroneities such as those between the effects of contemporaneous and evolutionary biological processes, and both early- and late-stage diagenesis respectively. Since our spatiotemporal frameworks integrated genetically-significant fabrics in textural evolution, the effects of particular biotic processes imparted differential controls on subsequent stages and mechanisms in diagenesis. This evolutionary concept genetically linked aspects of paleoecological-geochemical dynamics at various spatiotemporal scales. Hence, the relative fine grain-size of microfills and associated dolomites reflects the effects of diagenesis in distinct burow fabrics produced by selective deposit-feeding strategies (Keswani *et al.*, 1995; Keswani and Pemberton, 1997). These contemporaneous microphagous activities likely influenced dolomitization both directly and indirectly, through local and facies-scale textural and geochemical modifications that controlled permeability characteristics, and spatial distribution patterns in nucleation sites and organics. Hence, the organogenic model for dolomitization outlined in Compton (1988), Slaughter and Hill (1991), Soussi and M'Rabet (1994) and Wright (1997) requires further consideration. Details of integral paleobiological parameters in these genetic interplays represent the focus of our future research.

CONCLUSIONS

This paper proposes a conceptual model comprised of genetic and spatiotemporal frameworks that link constructional elements of textural relationships in ancient detrital carbonate deposits. Our model is based on the fundamental premise that both physical and mineralogical characteristics of constituent fabrics generate cumulative effects of direct genetic interplays and indirect feedback interactions, and spatiotemporal relationships in textural evolution. This concept models aspects of texture genesis, and associated unique and overlapped spatiotemporal dimensions as inseparable entities in evolutionary dynamics. Such an holistic approach in textural modelling, facilitated construction of conceptual frameworks that integrated both genetic and spatiotemporal dynamics. This model depicts aspects of textural evolution in a three-dimensional, genetic framework that includes sedimentologically-, paleobiologically- and geochemically- produced fabrics, and respective spatiotemporal elements in a correlative bar-scale paradigm. Since textural relationships have been modelled as products of such dynamical interactions, the proposed frameworks furnish a conceptual base for interpretations of genetic linkages in fabric evolution. Therefore, our model establishes inter-relationships between texture genesis and diagenesis.

Applications of the proposed conceptual frameworks provides a useful vehicle for understanding the effects of paleoecological-geochemical dynamics, and in the construction of models for carbonate diagenesis. In particular, coupled genetic and spatiotemporal frameworks facilitate interpretations of the roles of paleobiological controls on dolomitization. This approach invokes classification of bioturbate textures and associated dolomite fabrics on the basis of genetic criteria. Thus, our model incorporates inferences on the roles of contemporaneous fabrics as intrinsic factors that influenced textural evolution, associated with progressive burial and late-diagenesis.

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CHAPTER 5

CONCLUSIONS

This thesis presents the initial results derived from an ongoing research program focused on the effects of bioturbation on carbonate diagenesis. A comprehensive understanding of these relationships in paleoecological-geochemical dynamics, particularly paleobiological controls on mechanisms of dolomitization, provides information useful in hydrocarbon exploration and development. An holistic approach to fabric analysis on the basis of paleobiological criteria, facilitated construction of a new conceptual model for understanding these relationships in texture genesis and diagensis. Applications of this model in future research will likely provide insights on the genetic relationships in textural evolutionary dynamics, and on origins and distribution patterns of paleobiologically-influenced dolomites.

Bioturbation produced textural modifications that consisted of both discrete structures and indiscrete fabrics. Yet, the conceptual foundations of proposed ichnofacies models and classification schemes for ichnofabrics are incompatible, and their scales of applications in sedimentology are somewhat arbitrary. Since the traditional ichnofacies concept has been applied successfully in paleoenvironmental reconstruction, and in understanding paleoecological dynamics, an extension of genetic principles to classification schemes for indiscrete bioturbate textures facilitated integration in a comprehensive model. This prerequisite of a genetic foundation prompted scrutiny of prior classification schemes, and applications of indiscrete bioturbate textures in paleoenvironmental reconstructions. A critical review of proposed schemes showed that classifications ranged from simple descriptive systemizations, and semiquantitative formulations;to complex mathematical and computer-based models. Furthermore, this examination showed that schemes proposed for ichnofabrics lacked a genetic basis for classification and rendered this concept incompatible to the ichnofacies model. This incompatibility hindered integration of ichnological data in a comprehensive model for genesis and diagenesis.

This thesis proposes a new integrated, conceptual model for texture genesis and diagenesis. The model integrates conceptual frameworks for both genetic and spatiotemporal elements manifested in textural relationships. Such a model links genetically, the effects of both direct interplays and indirect feedback dynamics in textural evolution. These effects consist of genetically-significant fabrics, modelled as respective elements of a three-dimensional framework, where the axes represent physiogenic, biogenic and diagenetic processes. Spatiotemporal dimensions associated with these genetically-significant fabrics constitute inseparable aspects, where relationships have been modelled in a concurrent framework. Correlations of both unique and overlapped spatiotemporal elements on paleobiologically-sedimentologically-, and on diagenetically-significant scales, established relationships in textural evolutionary dynamics. An understanding of these linkages in physical and mineralogical characteristics facilitates interpretations of controls on carbonate diagenesis. This model provides an integrated framework, particularly a new paleobiological approach useful for understanding intrinsic controls on dolomitization.